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In-Line Wear Monitor

Keith Pieper
Allison Gas Turbine Division
P.O. Box 420
Indianapolis, IN 46206-0420

Dr. Ivor J. Taylor
Princeton Gamma-Tech
1200 State Rd.
Princeton, NJ 08540

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Aero Propulsion and Power Laboratory
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Wright-Patterson Air Force Base, OH 45433-6563

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Phillip W. Centers

PHILLIP W. CENTERS, Ph.D., TAM
Lubrication Branch
Fuels and Lubrication Division
Aero Propulsion and Power Laboratory

Howard F. Jones

HOWARD F. JONES, Chief
Lubrication Branch
Fuels and Lubrication Division
Aero Propulsion and Power Laboratory

FOR THE COMMANDER

Leo S. Harootyan, Jr.

LEO S. HAROOTYAN, JR., Assistant Chief
Fuels and Lubrication Division
Aero Propulsion and Power Laboratory

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This report describes the construction and test results of an in-line monitor for critical ferrous and nonferrous metal debris in turbine engine lubrication systems. The in-line wear monitor (ILWM) has been developed by Allison Gas Turbine Division and a subcontractor, Princeton Gamma-Tech. The system uses the X-ray fluorescence principle for detecting metal debris on a continuous basis while the engine is running. The sensor portion of the system is engine mounted and contains a radioactive X-ray source, a flow cell to direct the oil across an X-Ray permeable window, a proportional counter X-ray detector and its associated preamplifier and amplifier electronics. The data acquisition electronics is mounted on the airframe and contains a microprocessor based system for inputting pulses from the sensor, classifying and counting them according to energy bands, and analyzing the data and outputting metal concentration values to the engine monitoring system.

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The sensor portion of the system is designed to fit on a TF41 turbine engine in place of a tube between the oil tank and the oil pump. A TF41 engine monitoring system (EMS) has been modified to accept the new signals from the ILWM on spare inputs so that none of the existing functions were disturbed.

The preamplifier board in the ILWM sensor has been redesigned to reduce vibration resonance effects. The ILWM System has been demonstrated for 272 hours on a TF41 Accelerated Mission Endurance Test. The sensor performed properly under actual engine vibration and temperature conditions.

The wear monitor system has been flow tested at various flow rates, concentration levels, oil temperatures, and aerations. The wear monitor detected iron, copper, and both iron and copper together with less than 2 ppm one sigma statistical uncertainty for 30 minute count times over the 0-50 ppm range. There was no significant effect of flow rate or aeration on accuracy. The sensor output was stable within 6 ppm for oil temperatures of 20°C to 100°C and for a constant high voltage (HV) to the X-ray detector tube. The change with temperature can be further reduced by closed loop gain control through varying the HV bias to the detector, and the curves defining how HV would have to be varied to correct the output over temperatures of -50°C to 100°C has been obtained.

Recommendations for further development are discussed. The system is developed to the point that it can be tested in an actual flight environment.

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I. INTRODUCTION

The purpose of this final technical report is to describe the technology of the In-Line Wear Monitor program. The technology described was developed during the time period 15 November 1985 to 30 April 1989 under Air Force Contract No. P33615-85-C-2537. This report mainly describes the results of work done after 30 June 1988. The results prior to that time are summarized in Section II of this report. More detailed results are covered in Interim Technical Report AFWAL-TR-88-2095 (Reference 1*).

The objective of this program is to design, construct, evaluate, and demonstrate an in-line monitor for critical ferrous and nonferrous debris in turbine engine lubrication systems under engine operating conditions.

The development of an effective monitoring system for wear debris would reduce the need for oil sampling followed by laboratory spectrometric analysis as now performed in the military Joint Oil Analysis Program (JOAP). This program builds on previous contracts sponsored by the Air Force (References 2 and 3) that demonstrated the detection of iron in oil using the X-ray fluorescence principle. This program goes beyond the previous programs by developing a sensor system that can be mounted on an engine and operate under the severe environment present on the engine. The aim of the program is to develop and engine demonstrate a device that with minor modification can be flight demonstrated in a follow-on program. Once the device is flight demonstrated, it can then be specified with some confidence for new engine programs. Because of the desire to eventually flight demonstrate the device, it was made compatible with an engine for which an engine monitoring system (EMS) was already available.

The underlying technology selected to detect the metallic debris in oil was X-ray fluorescence. The oil is irradiated by an X-ray source, and the X-rays strike the wear metal atoms in the oil causing them to emit secondary X-rays with an energy indicative of the type of metal and a frequency of occurrence indicative of concentration.

Section II of this report briefly describes program background and summarizes results of effort through 30 June 1988. Section III describes modifications made to the Engine Analyzer Unit of the TF41 EMS to accept the new inputs. Section IV reviews the changes made to the wear monitor sensor to make it less vibration sensitive. Section V describes the testing of the In-Line Wear Monitor system with a TF41 engine on a test stand. Section VI describes the testing of the wear monitor on a flow rig at various flow rates, oil temperatures, impurity concentrations, and with air in the oil. Section VII gives the conclusions and recommendations derived from this program.

*References are listed at the end of this report.

II. PROGRAM BACKGROUND

In November 1985, Allison started work on contract No. F33615-85-C-2537 to design, construct, demonstrate, and deliver a working model of an In-Line Wear Monitor (ILWM) for metallic debris in engine oil. The program activity is indicated in Figure 1. Initial sensor studies utilizing silicon X-ray detector technology indicated that hardware necessary to maintain the silicon detector at near cryogenic temperatures made it unlikely that a near flight demonstrable sensor could be developed in the time frame of this program. Subsequently, the use of proportional counter tube X-ray detectors was investigated by Princeton Gamma-Tech, who had access to improved proportional counter technology developed by their parent company, Outokumpu in Finland, and utilized on the previous program (References 2 and 3).

A block diagram of the system which was developed is shown in Figure 2. The sensor is engine-mounted and contains a radioactive X-ray source, a flow cell to direct the oil across an X-ray permeable window, a proportional counter X-ray detector and its associated analog circuitry, and preamplifier and amplifier electronics. The data acquisition electronics is mounted off-engine on the airframe and includes a peak detector, A/D converter, a microprocessor based section for keeping track of energy band counts and data analysis, high and low voltage power supplies, and system interface electronics. The data storage system section consists of existing TF41 EMS electronics that have been modified to accept the outputs of the data acquisition electronics and store debris concentration values on magnetic tape for long term trending.

The sections which follow summarize the mechanical design, electronic design, application testing, and vibration testing. A more complete description of these topics is contained in the Interim Technical Report (Reference 1).

2.1 SENSOR MECHANICAL DESIGN

This section summarizes the mechanical design of the sensor. The flow cell for the in-line wear monitor system was designed to fit in place of a tube going between the TF41 engine oil tank and the engine oil pump inlet. The flow cell has been designed with end tube sections identical to the tube it replaces and a cylindrical section in the middle of the tube as shown in Figure 3.

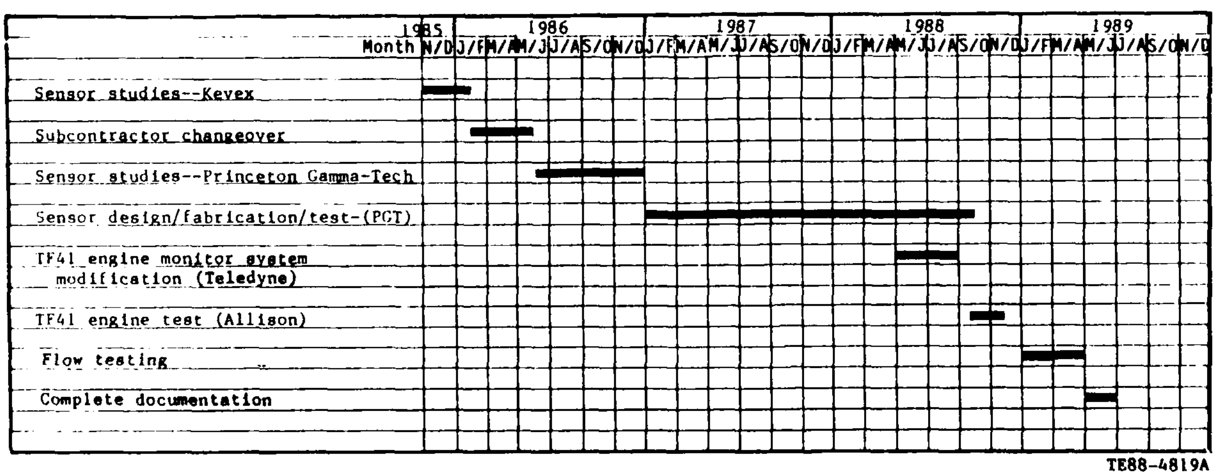


Figure 1. In-Line Wear Monitor program schedule.

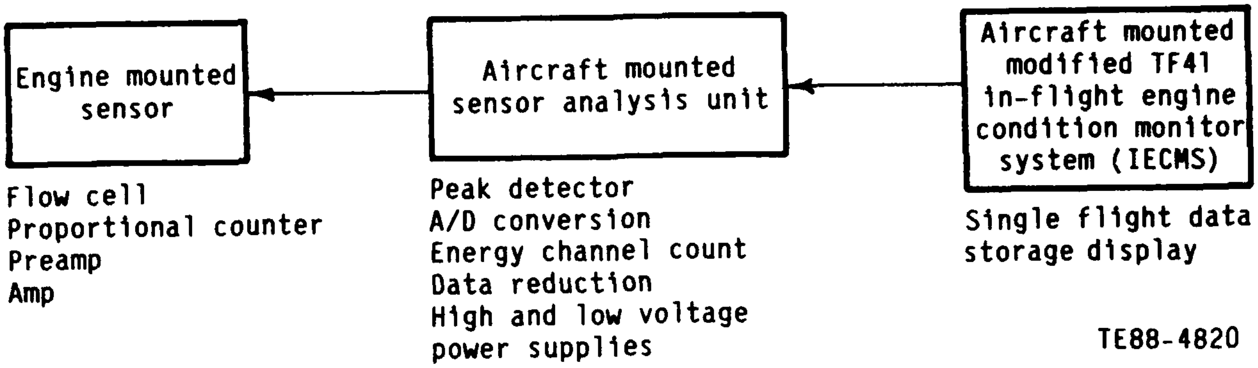


Figure 2. In-Line Wear Monitor block diagram.

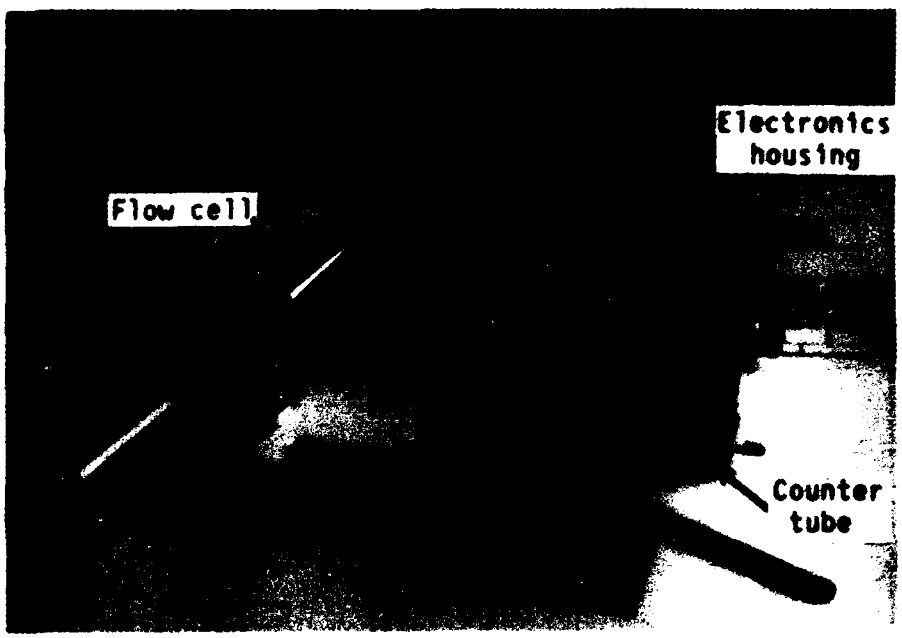


Figure 3. Flow cell, electronics, and counter tube.

A circular X-ray permeable window is placed over the circular opening on top of the flow cell and sealed by an O-ring. An anvil-shaped oil flow deflector is attached to the bottom lid and serves to evenly direct part of the oil flow across the X-ray window. The oil flow deflector has holes drilled in it parallel to the direction of oil flow and sized so that the cross sectional area available for oil to flow through is the same as the original tube.

The housing that contains the proportional counter tube, the radioisotope sources, and the amplification electronics is shown in Figure 3. The housing attaches to the flow cell and is designed so that if the X-ray window leaks, the housing serves as a secondary containment so that engine oil will not be lost. The special miniaturized proportioned counter tube, developed for this project by Outokumpu and also shown in Figure 3, consists of a stainless steel

tube lined with high purity aluminum, a high purity beryllium X-ray window, a thin anode wire down the center line of the tube, and a mixture of noble gases such as neon-argon. A high voltage is connected between the anode and the case so that when X-rays strike the gas mixture ion pairs are created and collected as a series of current pulses.

The printed circuit boards are made with a Teflon-based material so that they can survive 150°C without degradation. The boards are laid out using single-sided interconnections so that one side can be a ground plane to minimize microphonics.

2.2 SENSOR ELECTRONIC DESIGN

This section summarizes the electronic design of the wear monitor sensor and sensor analysis unit.

The high voltage power supply needed for the proportional counter tube was developed and demonstrated to have essentially no drift up to 120°C, which is adequate since it is contained in the off-engine mounted sensor analysis unit. The preamplifier circuit located in the sensor head utilizes a field effect transistor front end plus subsequent bipolar transistor gain stages and a low noise 100 megaohm metal film feedback resistor to convert the charge pulses from the proportional counter tube into millivolt level voltage pulses. The preamplifier was developed to be stable up to 150°C, which is adequate for the expected oil temperatures.

The sensor head also contains a signal processing amplifier with a fast channel for pile-up and live time correction. The amplifier stage increases signal levels from millivolt to volt levels so that signal can be transmitted through aircraft wiring with less chance of noise pickup.

A diagram of the electronics developed to process the pulse signals from the engine mounted sensor is shown in Figure 4. A peak detector is used to capture the peak value of the pulse from the sensor head amplifier. The peak value is digitized by a special A/D converter designed to avoid nonlinear effects of normal successive approximation converters. The digitized pulse value is used to increment the pulse counts of the corresponding energy band counter. After accumulating counts for a period of time, the results can be analyzed to separate intermetal effects and background effects. The resulting concentration values can then be supplied to the aircraft mounted engine condition monitoring system through the A/D converter or through the serial data output.

2.3 SENSOR APPLICATION TESTING

Initial sensor development efforts were focused on obtaining a design which had low enough background counts to allow detection of trace levels of iron in solutions. Iron contamination signals were seen from a variety of sources. Even pure grade beryllium foil used for the X-ray window can have up to 300 ppm iron, making it necessary to screen foils from several lots in order to find one with low enough iron content. Careful design of antiscattering baffles, source holders, and cell geometry was necessary to obtain minimum iron background and yet get a sufficient count rate from low ppm impurities in oil. A special low background proportional counter was developed by Outokumpu through

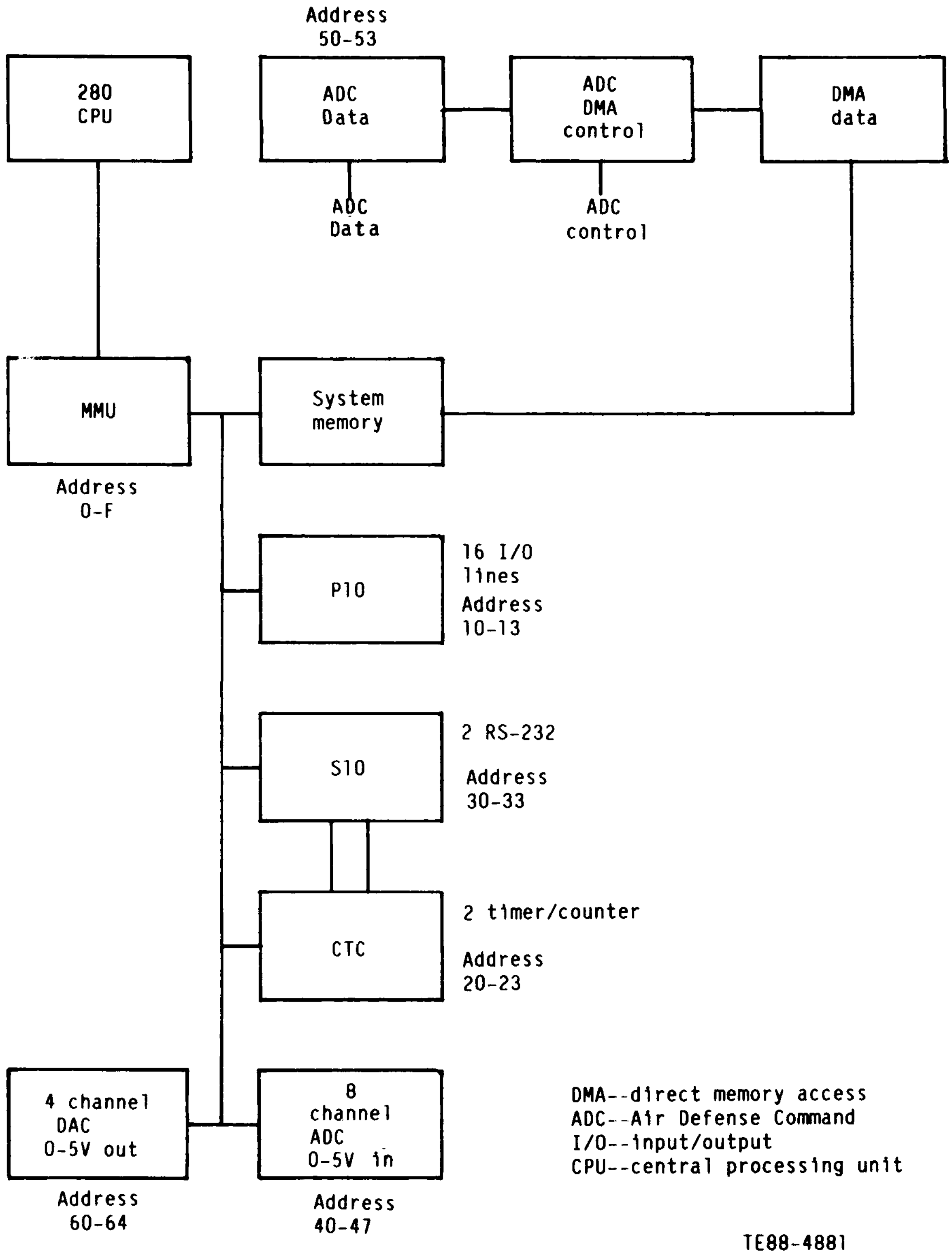


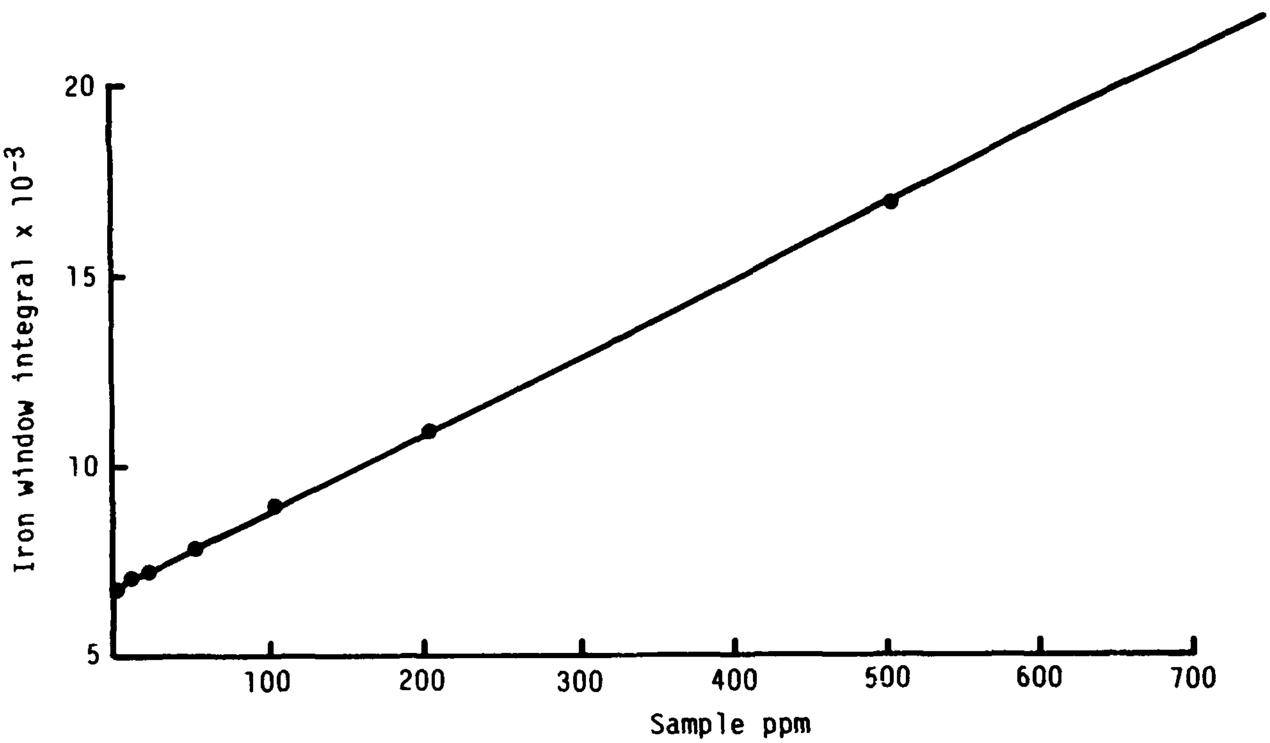
Figure 4. Data processing electronics block diagram.

proper design of edge shielding to the X-ray window on the counter, the structure and material of internal liners, and the uniformity of electric fields to minimize space charge effects in the ionization process.

Application testing with a low iron content beryllium window and water based samples indicated a statistical accuracy of around 6 ppm (6.1) for a 600 second analysis as shown in Figure 5. These results were obtained by the use of water based iron compound calibration standards. By comparing water based compound calibration standards with oil based standards on a commercial analyzer it was found the minimum detectable limit (MDL) in oil is about 3-4 times better than in water. This is due to X-ray penetration to greater depths in oil and less reabsorption of the iron energy band by oil than water. Thus the early application testing indicated the sensor had the capability of detecting iron to the 2-5 ppm level when using oil.

2.4 SENSOR VIBRATION TESTING

The sensor was next vibration tested on a shaker bench at Allison with a copper disk target using sinewave scans and random vibration profiles. The sinewave scans showed several frequencies where resonances would severely degrade the spectrum although the copper peak was still discernable. Random vibration testing showed a resonant frequency of around 20 kHz in the output baseline. When the proportional counter tube was disconnected, the 20 kHz resonance was still there. The prime suspect was gate structure vibrations in the field-effect transistor input component of the preamplifier. The conclusion from vibration testing was the preamplifier board needed to be redesigned to reduce vibration effects. The redesign and retest efforts are discussed in Section IV of this report.



600-sec analysis

Run	Sample ppm	Fe window integral	Baseline subtract	Analysis ppm
AL159	0	6,844 ± 83	0	
AL168	0	6,895 ± 83	0	
AL158	1,000	26,526	19,656	1,000 norm 19.65/ppm
AL161	20	7,269	399	20.3 ± 6.0
AL162	10	7,210	340	17.3 ± 6.0
AL163	50	7,999	1,129	57.4 ± 6.2
AL164	100	8,991	2,121	108 ± 6.4
AL165	200	10,922	4,052	206 ± 6.8
AL166	500	16,859	9,989	508 ± 7.8
AL167	750	22,016	15,146	770 ± 8.6
AL169	10	7,168	298	15 ± 6.0

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Figure 5. Data and response curve - clean beryllium window.

III. TF41 ENGINE MONITORING SYSTEM MODIFICATIONS

Rather than create a new system for long-term data recording and trending of outputs from the In-Line Wear Monitor, a TF41 EMS available at Allison was modified to accept the new signals. Similar EMS's are in use in the field on some A-7 aircraft models having Allison TF41 engines.

The EMS was modified by using spare inputs so that none of the existing functions were disturbed. This was done so that the system could be put on an A-7 aircraft for a flight demonstration in a follow-on program without disturbing existing EMS functions other than wiring harness additions. This section briefly describes the TF41 EMS and then describes the changes made to the EMS to accommodate the new inputs from the wear monitor.

3.1 TF41 ENGINE MONITORING SYSTEM DESCRIPTION

The A-7/TF41 EMS is an electrical/electronic system designed to monitor TF41 engine operation on the A-7 aircraft in order to:

- o improve flight safety
- o reduce maintenance costs
- o increase aircraft availability
- o increase mission effectiveness

The EMS consists of the following components which are added to the A-7 aircraft as a kit:

- o Engine-mounted transducer, plumbing, brackets, and interconnecting cables
- o Airframe mounted electronics called the engine analyzer set (EAS) consisting of an engine computer analyzer (ECA), a digital data indicator (DDI), and a mounting tray for the ECA. The ECA and DDI are shown in Figure 6.
- o An airframe change kit including cockpit and harness modification parts.

The EAS is manufactured by Teledyne Controls. EAS hardware is described in more detail in Reference 4 and software in Reference 5.

The other major component of the EMS is the ground station shown in Figure 7 which transcribes and analyzes data recorded by the airborne-mounted portion of the EMS on removable magnetic tape data cartridges. The ground station was designed by Allison Gas Turbine and is used with both the TF41 and the more recent A-427 EMS. The complete TF41 EMS is described in more detail in Reference 6.

3.2 MODIFICATIONS TO THE EMS FOR THE WEAR MONITOR

The Allison engine computer analyzer was modified by Teledyne to utilize two spare analog inputs and three spare discrete inputs to bring in the new wear monitor signals shown below in Table 1.

TABLE 1. Wear Monitor/ECA Interface Signals

Signal parameter	Signal type	Signal name, level, and description
ICON	Analog	Iron concentration 0-5 Vdc = 0-50 parts per million iron
CCON	Analog	Copper concentration 0-5 Vdc = 0-50 parts per million copper
WMFLT	Discrete	Wear monitor fault 0-5 Vdc range 0-0.8 Vdc = no wear monitor fault 2.7-5 Vdc = wear monitor fault
SLTIME	Discrete	Short time average/long time average 0-5 Vdc range 0-0.8 Vdc = short time average 2.7-5 Vdc = long time average
DSYNC	Discrete	Data sync signal 0-5 Vdc range 0-0.8 Vdc = Low 2.7-5 Vdc = High DSYNC goes from low-to-high when wear monitor system has just output new data which should be recorded. DSYNC goes high every 3 minutes and stays high 1 minute. Only one data record is taken after DSYNC goes high.

The software of the ECA was modified as follows:

- o Data input routines were modified to input and store the new input parameters listed in Table 1.
- o A new software block was added to analyze the new input parameters to determine when to request that data be recorded on tape and to analyze inputs for fault conditions. The new software block was inserted in the common logic section which is executed both in-flight and on the ground.
- o data display unit (DDU) routines were modified to display the current values of the new input parameters when requested through the DDU keyboard.

The new software block was set up to record data every 3 minutes provided the DSYNC signal had a low to high transition at 3 ± 0.1 minutes. If DSYNC becomes stuck low or high, the software was set up to take data after 3.1 minutes with a fault flag set. If DSYNC was found to be transitioning too often - such as might occur due to intermittent connections, noise, or defective circuitry - the software waits until an accumulated time of 2.9 minutes has passed and then takes a data record with a fault flag set.

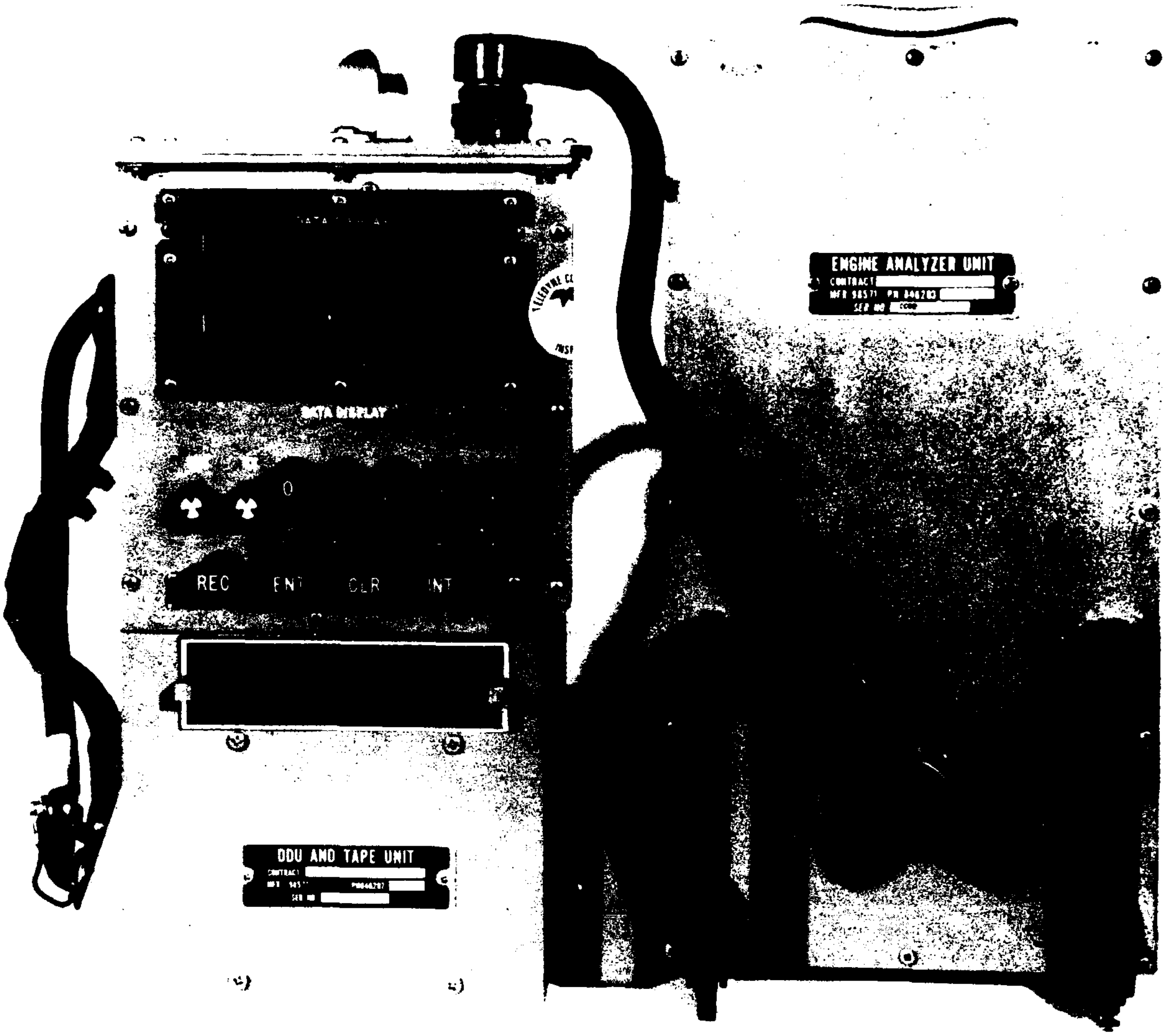


Figure 6. TF41 engine monitoring system digital data indicator and engine analyzer unit.

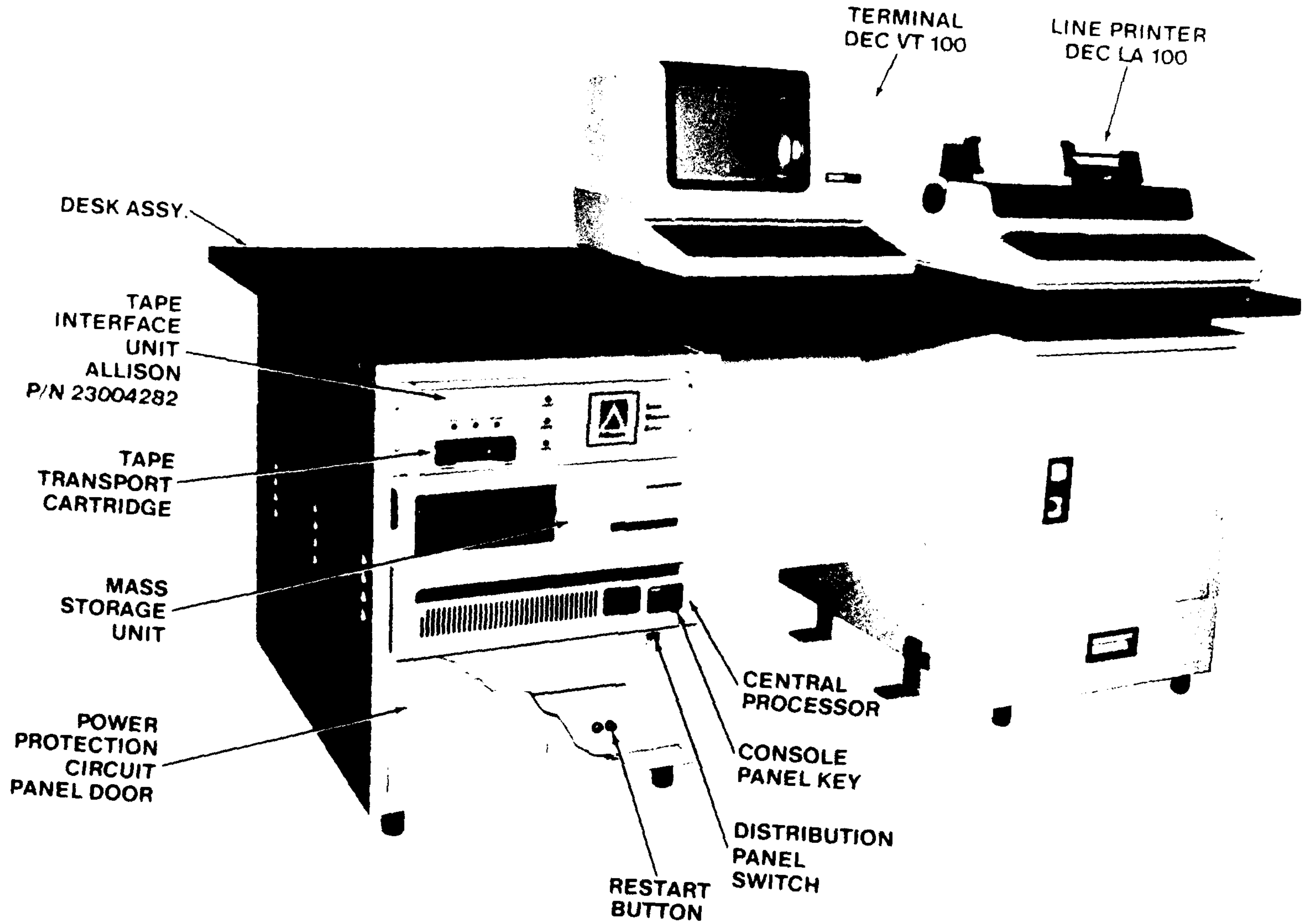


Figure 7. TF41 engine monitoring system ground station.

IV. SENSOR MODIFICATION AND RETEST

As a result of vibration testing, the preamplifier board in the wear monitor sensor was redesigned to provide better mounting of critical front end parts and to minimize wire lengths. The sensor with the revised preamplifier board was sensitivity tested with static oil/contaminant samples and still showed sensitivity on the order of $\pm$ 3 ppm. The sensor was tested at 125°C analyzing a copper foil sample and was found to be very stable. Spectrum peak shift was only 130 electron volts which indicates that auto correction by the microprocessor in the sensor analysis unit (SAU) would only have to adjust the high voltage supply setting within a 3 volt range and in fact, the system could be operated at constant high voltage on the proportional counter since peak shift was only approximately one-tenth of the peak width. The circuitry appeared less sensitive to microphonics than the previous circuit based on observations of the output while rapping the sensor on the table.

The sensor was then shipped to Allison for vibration and engine testing. The sensor was first tested on a shaker table with no high voltage (HV) applied and a NAVMAT random vibration profile of 0.03 g^2/Hz applied. The sensor's slow channel output had up to 10 V noise peaks but there was no strong 20 kHz noise was present on previous testing. It was felt that the SAU would be able to filter out the remaining noise, and it was decided to proceed with testing the unit on the TF41 engine.

V. WEAR MONITOR SYSTEM ENGINE TESTING

An opportunity arose to test the sensor on a TF41 engine on a test stand at Allison instead of on a later J-57 engine test at Wright Patterson A.F.B. as originally planned. The TF41 engine was being assembled for an accelerated mission test (AMT) endurance test. The test was planned to include 320 hours of engine running time, and oil samples were to be taken periodically from three places in the engine to check for wear. This section describes the vibration evaluation, the test setup, and the results of engine testing.

5.1 VIBRATION EVALUATION

The sensor was first tested on the engine with only the low voltage supply applied and no other analysis electronics hooked up to determine if the output looked clean enough to justify shipping all the analysis electronics to Allison. Figure 8 shows the sensor installed in TF41 engine S/N 908. The sensor fits in place of a tube which goes between the oil tank and the oil pump.

The backshell of the low level connector interfered with a nearby tube and had to be removed. Cloth tape was used to seal the back and to keep the insert in place. During engine running, the sensor's slow channel output with no HV applied exhibited 0.2 V peak-to-peak typical noise with occasional 0.6 V peaks and again no strong 20 kHz components.

Prior to installation on the engine, the sensor had been instrumented with accelerometers on all three axes. Typical vibration profiles are shown in Figures 9 and 10 at idle speed and Figures 11 and 12 at intermediate power. These signals were monitored throughout engine running, and vibration levels on the sensor never exceeded more than 5 g's at any frequency. These results indicated that the sensor had a good chance of working properly. Therefore, the electronic hardware for analyzing and storing data from the sensor was shipped to Allison from PGT.

5.2 ENGINE TEST SETUP

A block diagram of the analysis electronics test setup is shown in Figure 13 and a photograph of the analysis electronics is shown in Figure 14. The SAU is a complete microprocessor based unit which inputs and processes the raw sensor signal and outputs two analog concentration signals and three discrete signals for data synchronization and status indication. The SAU also has a serial data link which was used to store the energy channel counts on the hard disk of a personal computer (PC). The two analog outputs were continuously plotted on a strip chart recorder. The interface of the SAU outputs with the modified EAU used in the TF41 EMS was also demonstrated. The SAU was set up to automatically accumulate X-ray counts for 12 minutes, output data to the analog outputs and PC hard disk, and then reinitialize and start over again.

A commercial PGT System III sensor spectrum analyzer was also hooked up and operational during the engine test to provide an independent means of inputting and analyzing the sensor data. User sequence software was devised to automatically accumulate X-ray counts for 30 minutes, store the results on the system's 8 inch floppy disks, and then reinitialize and start over.

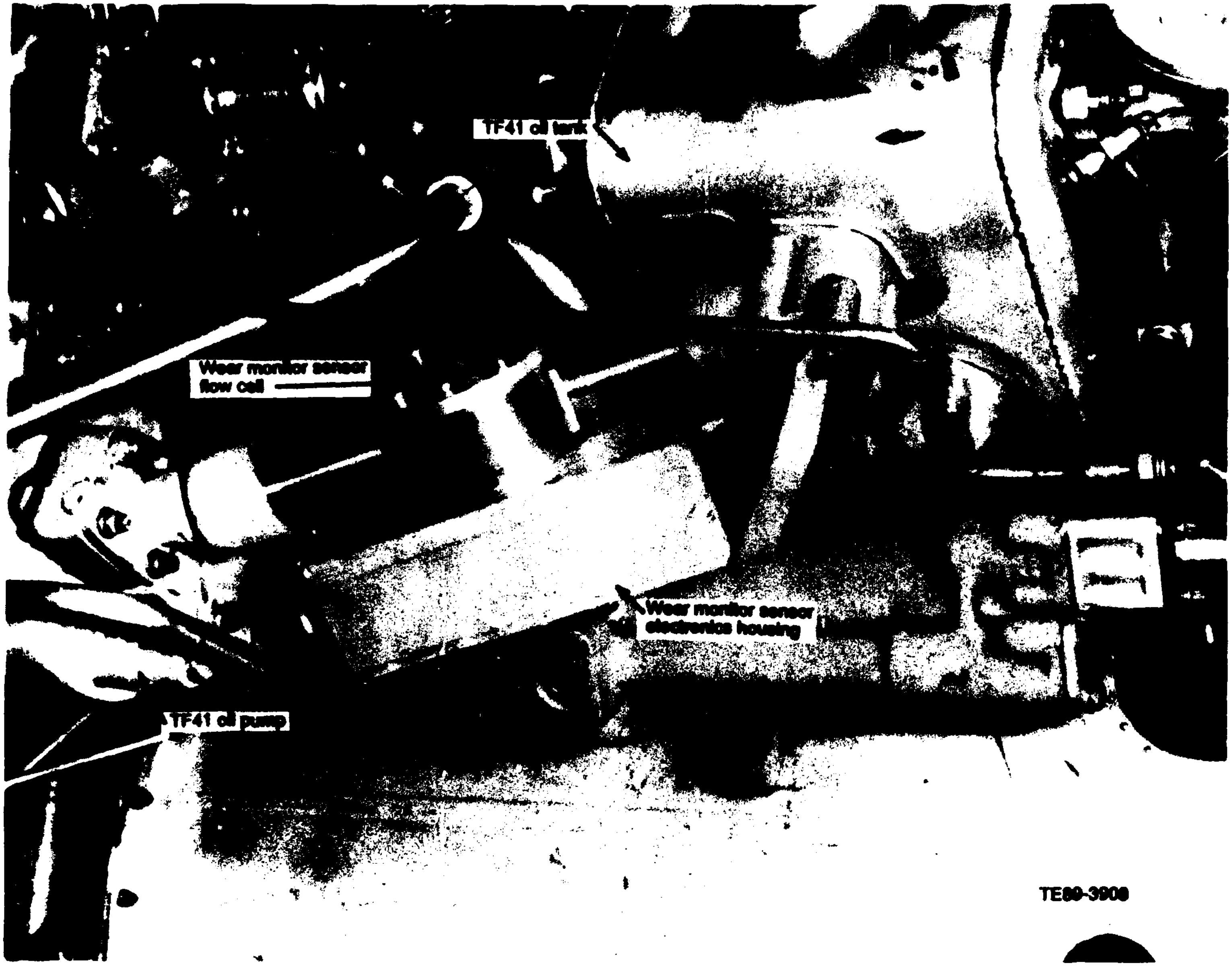
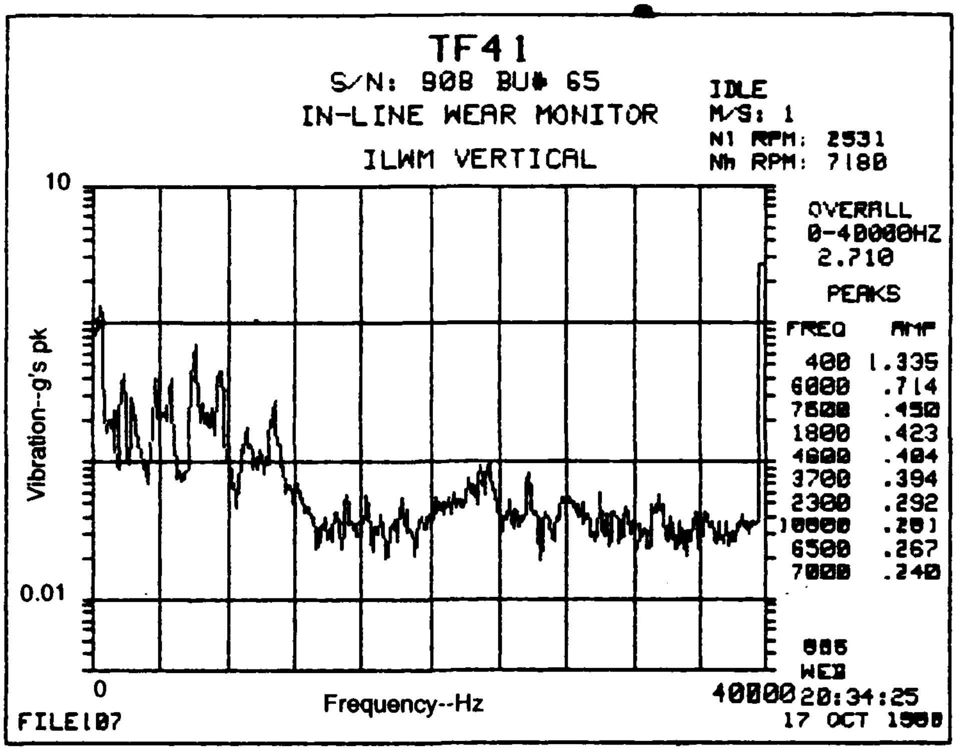


Figure 8. Wear monitor sensor installed on TF41 engine.



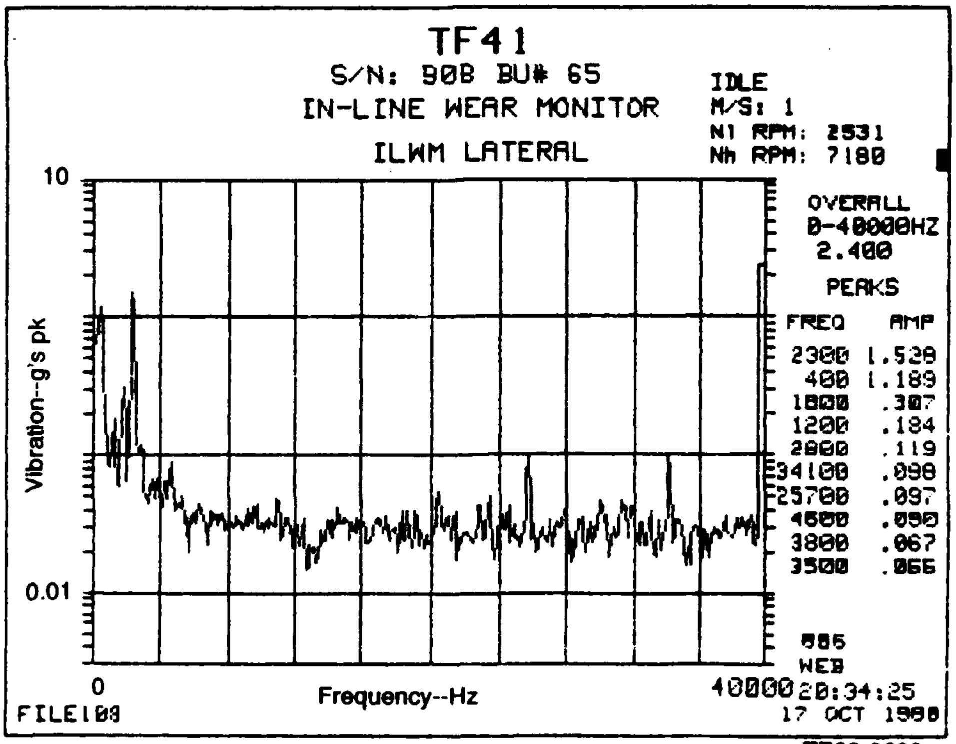


Figure 9. Vibration profiles at idle speed - vertical and lateral axes.

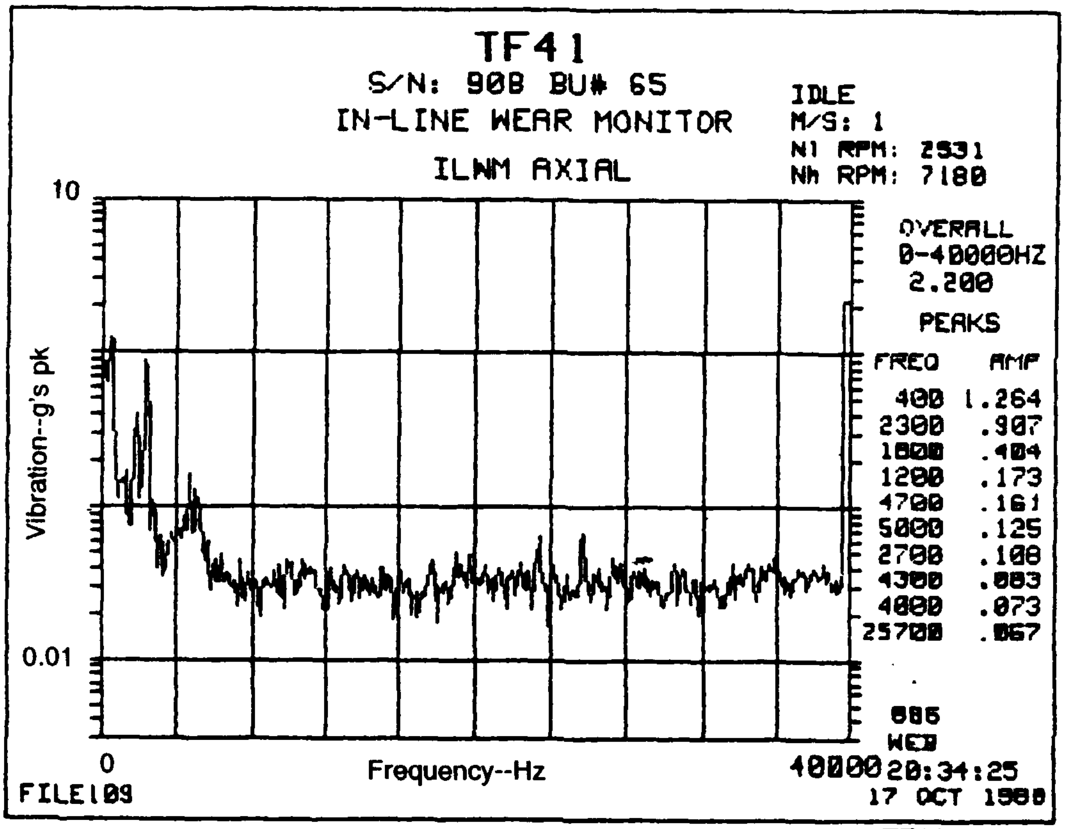


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Figure 10. Vibration profile at idle speed - axial axis.

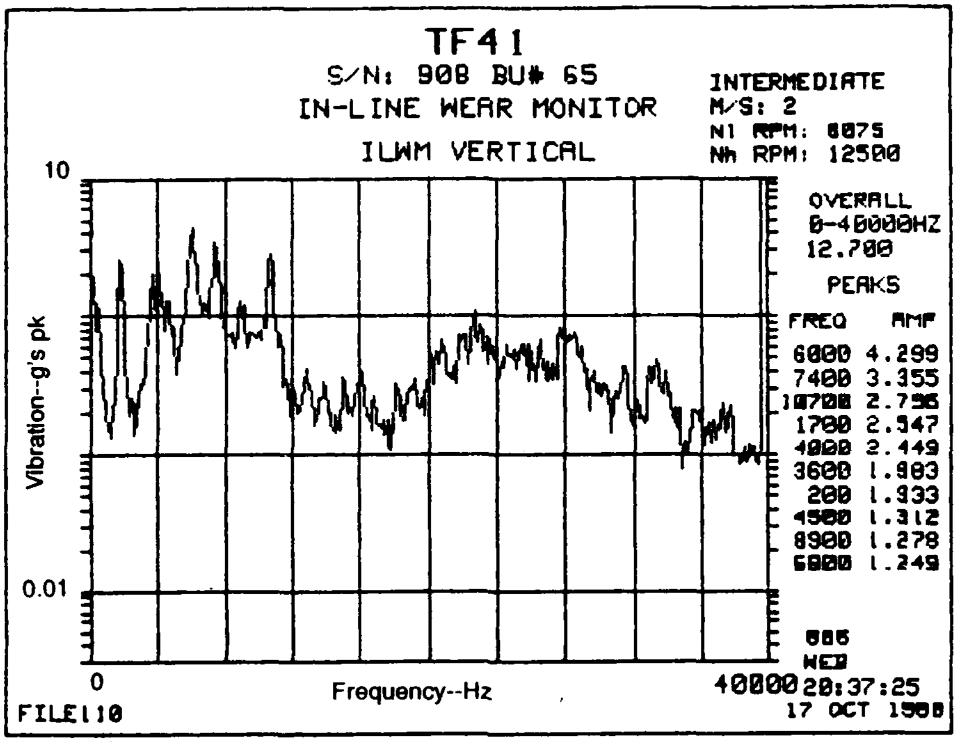
The sensor contained a device to measure the temperature of the air inside the sensor. During engine running, the indicated temperature was around 50°C.

5.3 ENGINE TEST RESULTS

A spectrum taken with the System III analyzer after it was first hooked up and while the engine was being cycled between 60 percent and 100 percent test power level is shown in Figure 15. The spectrum appears normal and has low background and a small but discernable peak in the iron region. A second spectrum taken when the engine was shut down for a 150 hour borescope inspection appeared the same, indicating very little effect of vibration on the spectrum.

When the engine was restarted, the sensor output was found to be very noisy. The engine was shut down and the sensor examined. There were black chafing marks on the cable connector, and a wire was broken inside the connector. After the wire was repaired and the connector was reattached, the sensor was operational but the output was more sensitive to engine vibration. A spectrum taken with the engine at full power, Figure 16 shows noise at low spectrum energies. The data in the iron region is not affected by the low energy noise, however, and the sensor iron and copper outputs are still acceptable. At idle speeds, the low energy noise was not present.

The microprocessor based sensor analysis unit exhibited better noise immunity than the System III analyzer due to the architecture of the analog-to-digital converter (ADC).



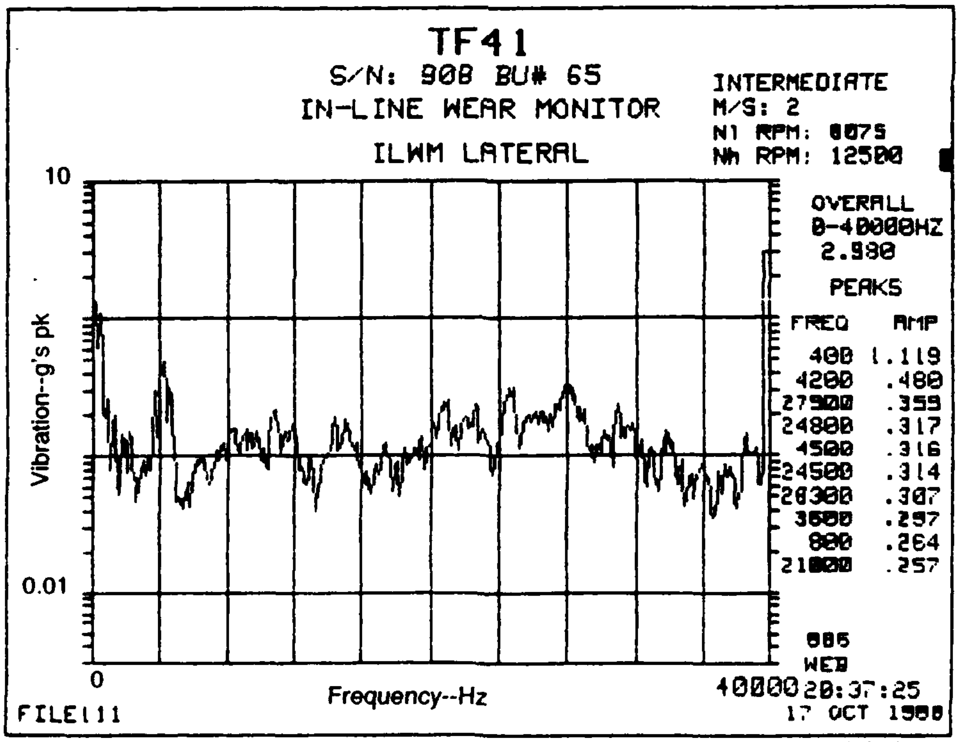


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Figure 11. Vibration profiles at intermediate power - vertical and lateral axes.

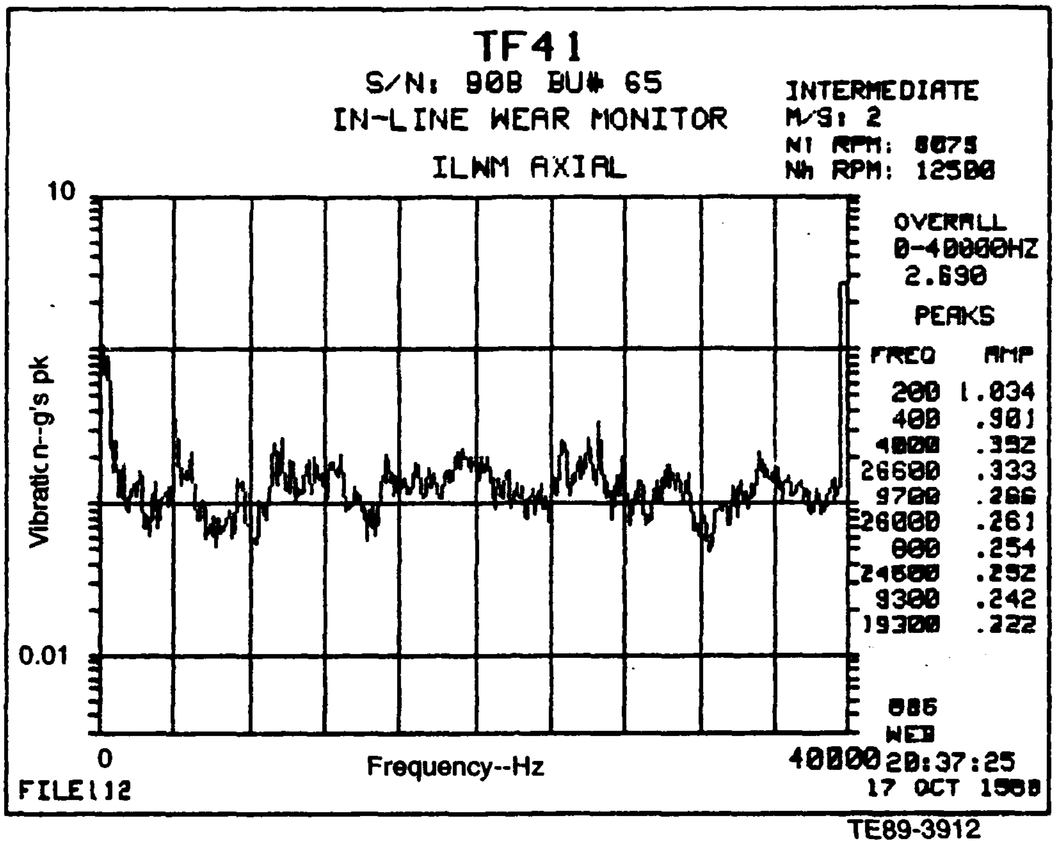

Figure 12. Vibration profile at intermediate power - axial axis.

Whereas the System III is generally used in the field of high resolution, X-ray spectrometry with solid state detectors, the ADC in the microprocessor system was designed to be gated by signals from a "fast" analysis channel in the sensor amplifier.

The sensor amplifier has two channels, a "slow" one for spectroscopy and a "fast" one for gating and timing (pile-up rejection, livetime correction, etc.) capability. The primary signal pulses from a proportional counter have a relatively fast risetime. The space charge effects in gas proportional counters on the other hand produce pulses of slower risetimes, which also contribute to system background as a result of ballistic deficit in the analysis channel.

By gating the ADC with the fast channel signal, a form of risetime discrimination is imposed on the overall system. Pulses introduced by microphonic noise sources also have a slow risetime and are not amplified through the fast channel. Consequently microphonic background noise is reduced since the slow channel analysis pulses due to microphonic sources are not processed by the gated ADC.

The microprocessor unit is capable of storing multiple spectra and can output data files to a host computer. Software was written at PGT to enable graphics presentation of spectra on an IBM XT computer.

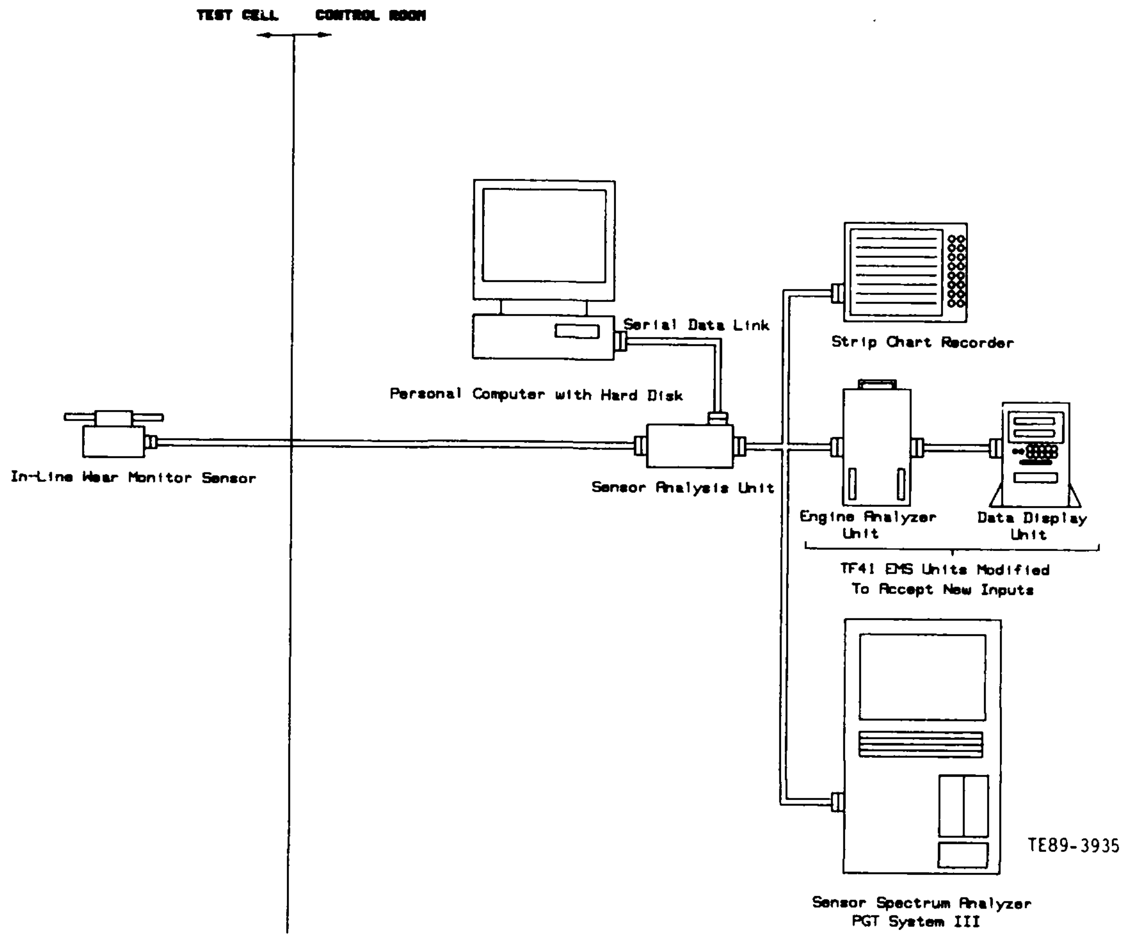

Figure 13. Analysis electronics test setup block diagram.

The spectrum shown in Figure 17 is such an output from the microprocessor unit, taken with the TF41 engine in shutdown condition. The iron and copper count regions are indicated, and the two peaks to the right of these regions are backscatter from the radioactive sources. Figure 18 is with the engine at 12,325 lb thrust. When compared with the spectra from the PGT System III analyzer, Figure 16, the low level background noise is seen to have been completely eliminated. Spectrum details are very well maintained in the microprocessor analysis.

The background noise will still obviously have an effect on the sensor resolution performance, and this is seen as a worsening of resolution in the Figure 18 spectrum, namely broadening of the backscatter peaks and reduced peak to valley ratio between the backscatter peaks, exactly as for similar spectrum taken with the PGT System III analyzer. However, in all cases, the iron analysis region was not significantly compromised.

The microprocessor was encoded to output "window" region integrals as drawn approximately in the Figure 17 spectrum. Fixed background level constants were subtracted from the integrals and the resultant values decoded through D/A converters in the microprocessor system and transmitted to pen recorders at Allison to present iron and copper analysis trends throughout the engine tests.

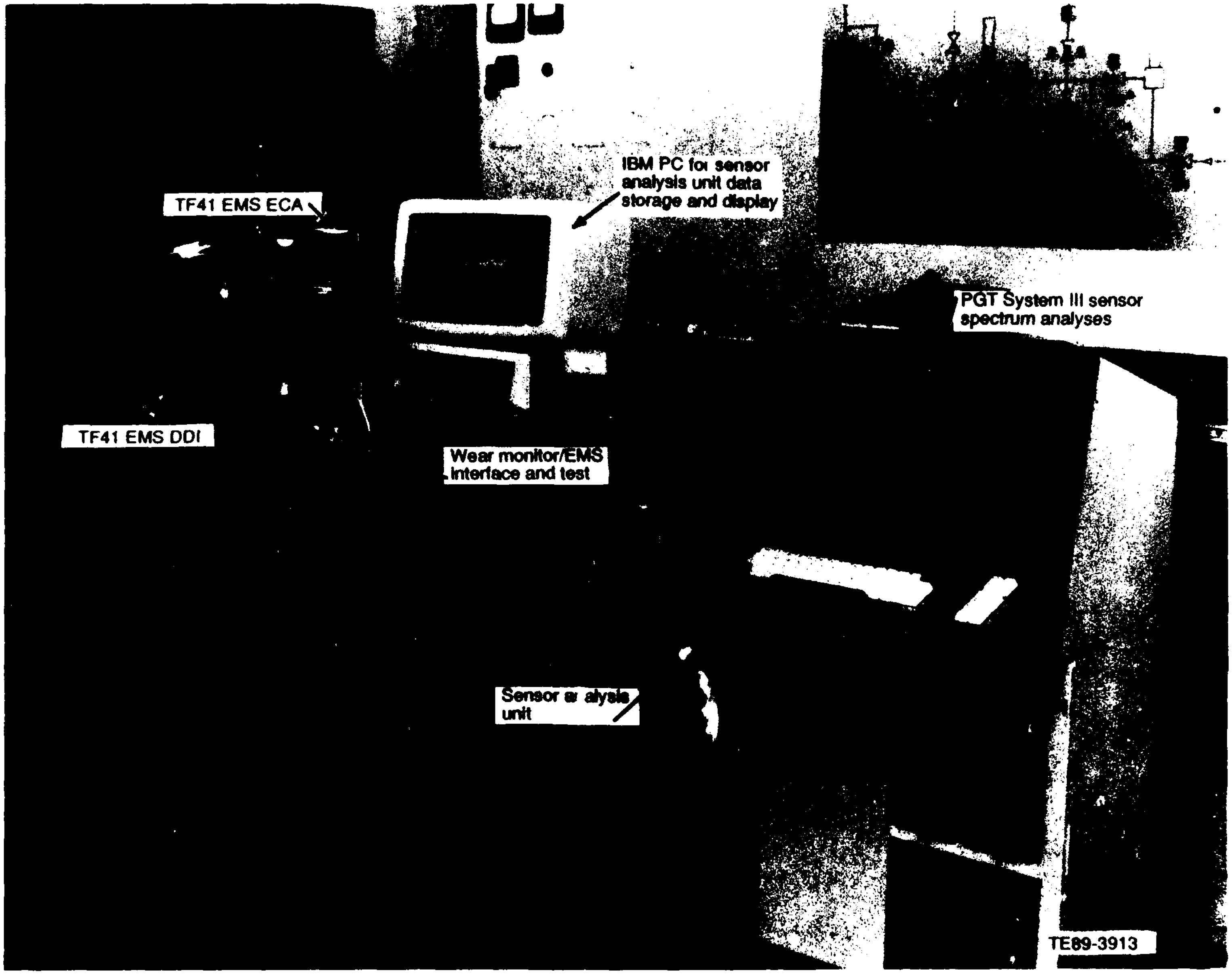

Figure 14. Analysis electronics test equipment.

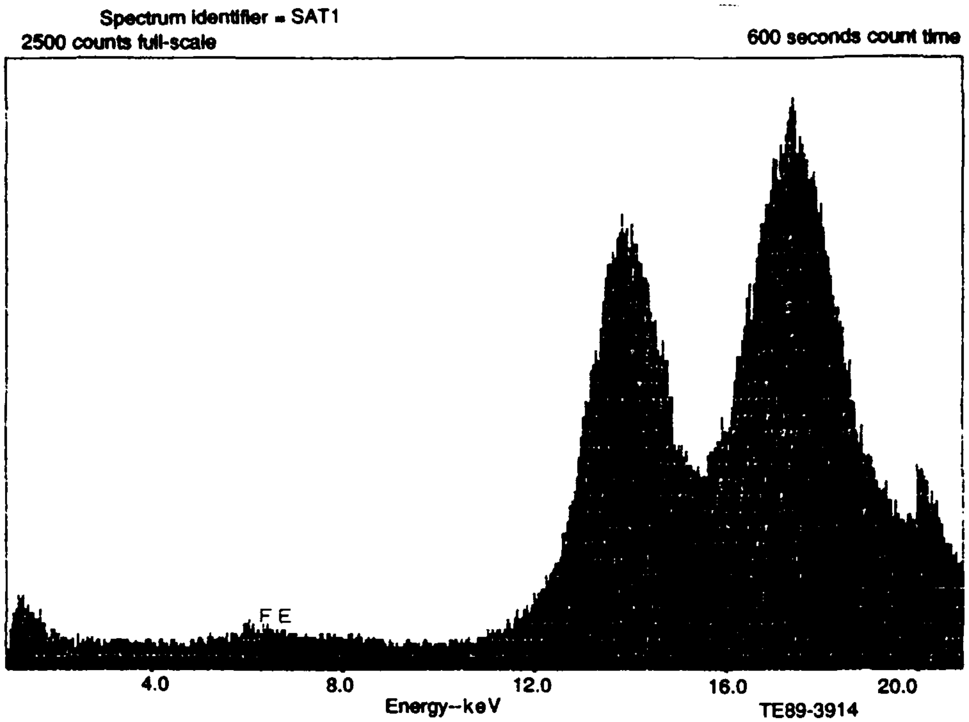

Figure 15. PGT System III spectrum for 60-100 percent engine power.

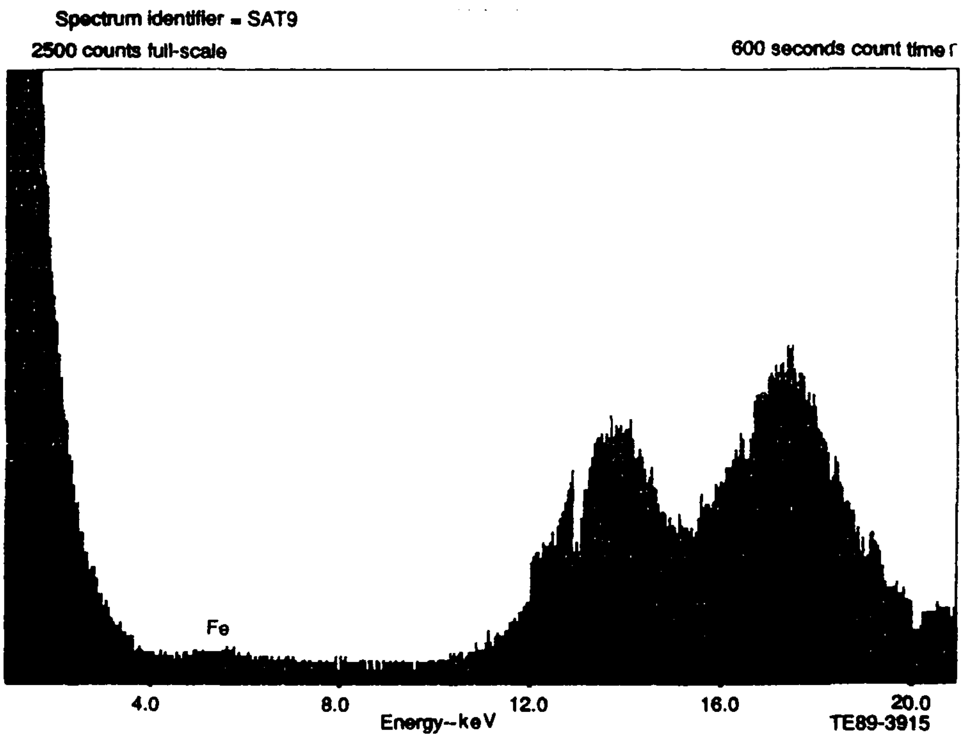

Figure 16. PGT System III spectrum for full engine power.

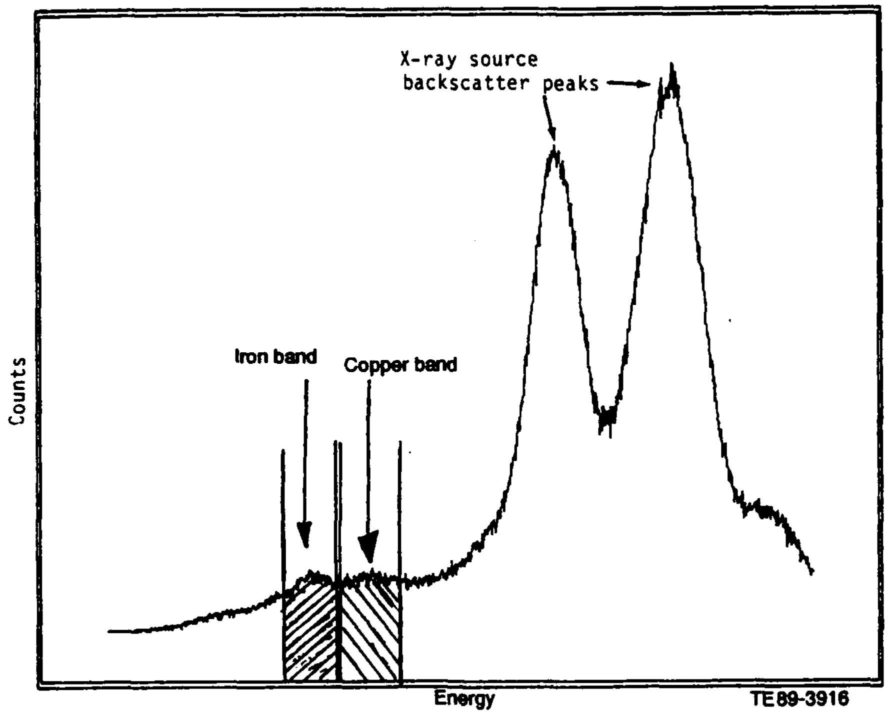

Figure 17. Sensor analysis unit spectrum for engine off.

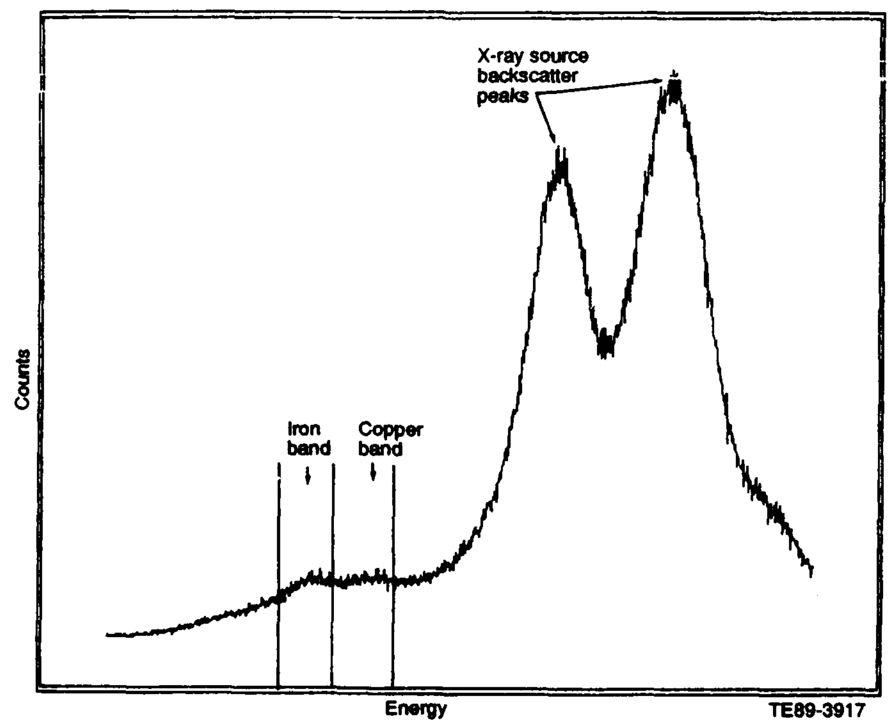

Figure 18. Sensor analysis unit spectrum for engine at full test power.

The sensor and overall system performance in these engine tests is considered to be extremely encouraging. The residual levels via Spectrometric Oil Analysis Program (SOAP) analysis seem to be around 1 to 2 ppm iron during this test period, and the spectra compare quite well to analysis of such levels as shown earlier in the Interim Report (Reference 1).

A summary of the engine testing is shown in Table 2. The sensor was mounted on the engine for a total of 272.6 hours of running time. Oil samples were taken approximately every 25 hours for SOAP evaluation. The SOAP results showed iron concentration of 5 ppm at the start of the engine test, decreasing to 1 ppm after 87.6 engine running hours. The iron concentration remained at 1 ppm except for one incident on 4 November 1988 when the engine shutdown due to a mag plug indication. This was later discovered to be due to a failure of the automatic oil addition system which dumped excess oil into the engine and stirred up debris. Three metal slivers and several chips were found on the mag plug. The SOAP sample taken immediately afterwards indicated 3 ppm iron.

Neither the System III nor the sensor analysis unit analog outputs indicated a significant shift in output probably due to the short length of time the debris was present before shutdown and to the fact that 3 ppm is about the minimum resolvable change in concentration.

As shown in the engine testing summary, the software on the PC system was corrected on 9 November 1988 to continuously store all previous data. Up to that point, it was only storing the six most recent spectra from the SAU.

5.4 ENGINE TEST DATA ANALYSIS

After engine testing was completed, the data from the following sources was collected and correlated:

- o System III floppy disks which had recorded the System III's X-ray spectrums taken over half-hour intervals
- o The personal computer's hard disks which had recorded the X-ray spectrums taken by the SAU over 12 minute intervals
- o The strip chart outputs which had recorded iron concentration, copper concentration, the data sync signal, and engine speed throughout the engine test
- o The engine test log which had recorded engine status and conditions

The total X-ray counts from all the energy channels in the iron band and in the copper energy band were obtained for both the System III data and the SAU data. The following conclusions were obtained from the data analysis:

- o When the engine was shut down and allowed to cool to a low ambient temperature of about 30°F, the concentration outputs shifted up the equivalent of about 7 ppm. Although much effort had been made to stabilize the sensor going hot, cold testing had not been performed prior to engine testing due to time limitations. This effect needed to be investigated during follow-on calibration testing (see Section VI).

TABLE 2. Summary of Engine Testing

Date	Condition	Total engine time - hours (elapsed hours)	Endurance cycle time - hours
	Engine to test stand.	7838.6 (0)	2.7
10/ 7/88	First oil sample - - 4 ppm Fe, 1 ppm Cu	7841.3 (2.7)	
10/19/88	Fourth oil sample - 2 ppm Fe, 1 ppm Cu	7903.6 (65)	32.8
10/19/88	Wear monitor sensor installed on engine	7903.6 (65)	32.8
10/27/88	PGT System III hooked up	8006.3 (167.7)	130.1
10/27/88	Wear monitor system cable wire repaired	8009.6 (171)	130.1
10/28/88	Microprocessor SAU and strip chart recorder output hooked up	8012.2 (173.6)	130.1
11/ 4/88	Engine shutdown due to mag plug. Caused by excess oil in engine due to failure of auto oil addition system - 3 ppm Fe, less than 1 ppm Cu	8087.0 (248.4)	197.4
11/ 9/88	PC hard disk storage software corrected to allow long term storage of SAU data	8140.3 (301.7)	251.0
11/11/88	End of endurance run	8175.3 (336.7)	285.5
11/11/88	End of post endurance run	8183.2 (344.6)	285.5

o During engine running at higher power points there was little effect of vibration induced noise on the iron and copper counts. However, a review of recorded data showed that the System III metal counts went up by approximately 40 percent whenever the engine was near 7,800 rpm NH and 3,000 rpm NL for a significant portion of the count time. For these same conditions the SAU data would tend to go down the equivalent of 2-4 ppm although this variation is near the minimum detectable limit.

The interface of the SAU with the TF41 EMS ECA which had been modified to work with the SAU was demonstrated towards the end of the engine test. The DDI did correctly read out the new variables and the iron and copper concentration values were recorded on the magnetic tape. However, later analysis of the tape

showed that the data was being stored at the maximum rate of once per second instead of once every 3 minutes. From analysis of the tape data it appears this was due to other EMS function inputs being open, which caused their logic to detect a fault condition and request data records more often. Further analysis and perhaps addition of these other engine inputs to the interface box are needed.

Since only 2-3 ppm of engine wear material was present throughout engine testing, as verified by SOAP samples, no trends were observed. However, the engine test showed the wear monitor system to be a major step forward since the sensor survived and performed properly under actual engine vibration and temperature conditions. The next step of the program was to complete sensor application testing with flowing oil.

VI. WEAR MONITOR FLOW TESTING

The last task of the program consisted of testing the wear monitor system on a flow test rig at various flow rates, concentration levels, oil temperatures, and aerations. This flow test rig, shown in Figure 19 was built at Allison and is capable of circulating up to 10 gpm of MIL-L-23699 oil through the wear monitor sensor. The rig utilizes a Wilden air operated diaphragm pump and all stainless steel fittings, valves, and tubing. All wetted parts of the pump were made of Teflon which avoids contamination of the oil by wear of metallic parts in the pump. The flow test rig was shipped to Princeton Gamma-Tech (PGT) for flow testing in order to utilize the laboratory grade X-ray fluorescent (XRF) equipment available for analyzing oil sample iron and copper concentration levels.

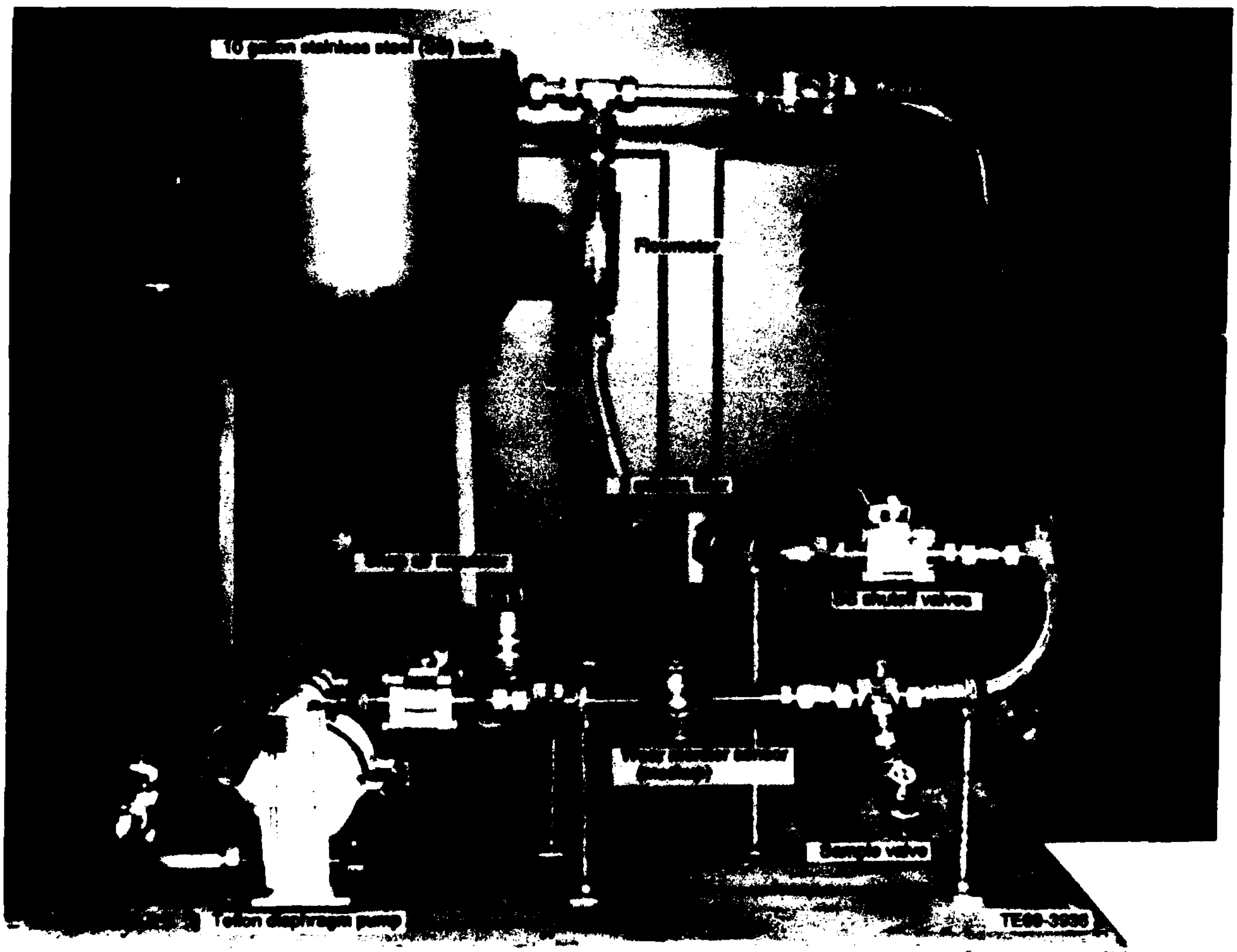

Figure 19. In-Line Wear Monitor flow test rig.

6.1 FLOW RIG MODIFICATION AND IRON TESTING

Heater bands were attached to the system pipes and the oil temperature varied under control of a thermocouple sensor mounted in the oil hopper. Up to 1800 watts of heater power were required to maintain the oil system constant at 100°C, under pumping conditions.

The parameters investigated were sensor performance with flow rate, with oil temperature at constant flow rate, and the effects of aeration of the oil. The system was loaded with 2 gallons of Mobil Jet 2 MIL-L-23699 oil and Conostan metallo-organic standards of 1000 ppm iron in oil matrix were used to "spike" the oil to varying levels of ppm iron concentration. Small samples were tapped off from the system during each run and analyzed with XRF analytical equipment by the PGT Applications Group.

There were some problems with the system during flow testing. The original beryllium window foil which was the same one used throughout the engine tests at Allison developed a leak and flooded the sensor with oil. The sensor had been designed to contain oil during a possible window failure, and certainly worked as planned in this regard. The sensor was washed out with methanol and freon and operation was resumed with no problems. The beryllium foil had a crescent shaped crack around the circumference, and it is suspected that it might have been damaged during incorrect assembly into its recess in the cell body. However, because this might have been a fatigue fracture, a separate test of a window assembly was made, using a micrometer gauge probe on the center of the beryllium foil. Total displacements of almost 1/16 inch were measured at the center of the window, although there were no failures. The air driven pump is a little unsatisfactory in this application. It is a pressure diaphragm pump and pulses the oil strongly.

In an attempt to eliminate this effect the sensor was relocated below the oil hopper on the intake side of the pump. This also gave deflection pulses at the window, now related to suction strokes of the diaphragm pump, so there may not have been any significant improvement.

The original beryllium foil was a good one in regard to low level of contaminant iron. The first replacement foil tried was very bad in this regard. A total of 26 foils from different batches of beryllium windows (used in a PGT product) were analyzed by XRF equipment before a replacement was found equivalent to the original foil. This confirmed entirely what had been encountered earlier in this project (Reference 1) namely that iron contamination in beryllium foils can vary widely, and foils need to be selected carefully.

The residual iron peak in the spectrum for the base oil is largely due to iron contaminant level in the beryllium window of the flow cell, as shown in Figure 20 and 21. The sensor with the new foil window ran through all the tests, taking several weeks, with no problems.

As in the engine tests at Allison, the sensor was linked to the microprocessor data acquisition unit with data transfer to an IBM personal computer for spectrum display.

The sensor was also linked to a PGT System III analyzer, allowing spectrum display and storage to disk and allowing programmed analysis runs.

The spectra were quite good, similar to those shown earlier in this work. For example Figure 20 shows the spectrum of the baseline oil at a flow rate of 8 gallons per minute through the cell compared with the spectrum for the oil spiked to 50 ppm iron level, also at 8 gallons per minute flow rate. Since in this work the area of interest is primarily in the low level response of the sensor, levels above 50 ppm iron were not run. A 50 ppm level is clearly identified, as shown in Figure 21.

As in previous work an iron "window" was set between 5.6 KeV and 7.2 KeV in the spectrum. A copper "window" was set between 7.24 KeV and 8.84 KeV. The sensor is able to separate iron and copper, and using the above energy regions no overlap correction was made to the data. A copper analysis in the presence of 50 ppm iron was made, as described in Section 6.3.

Figure 22 shows the sensor response to varying iron contaminant levels. At each point of iron standard addition the oil was circulated by pumping for almost 1/2 hour to ensure adequate mixing. Data runs were 30 minutes duration. The numbers relate to window integral counts in the iron region, and the size of the circle is close to the one sigma statistical uncertainty, including background level statistics.

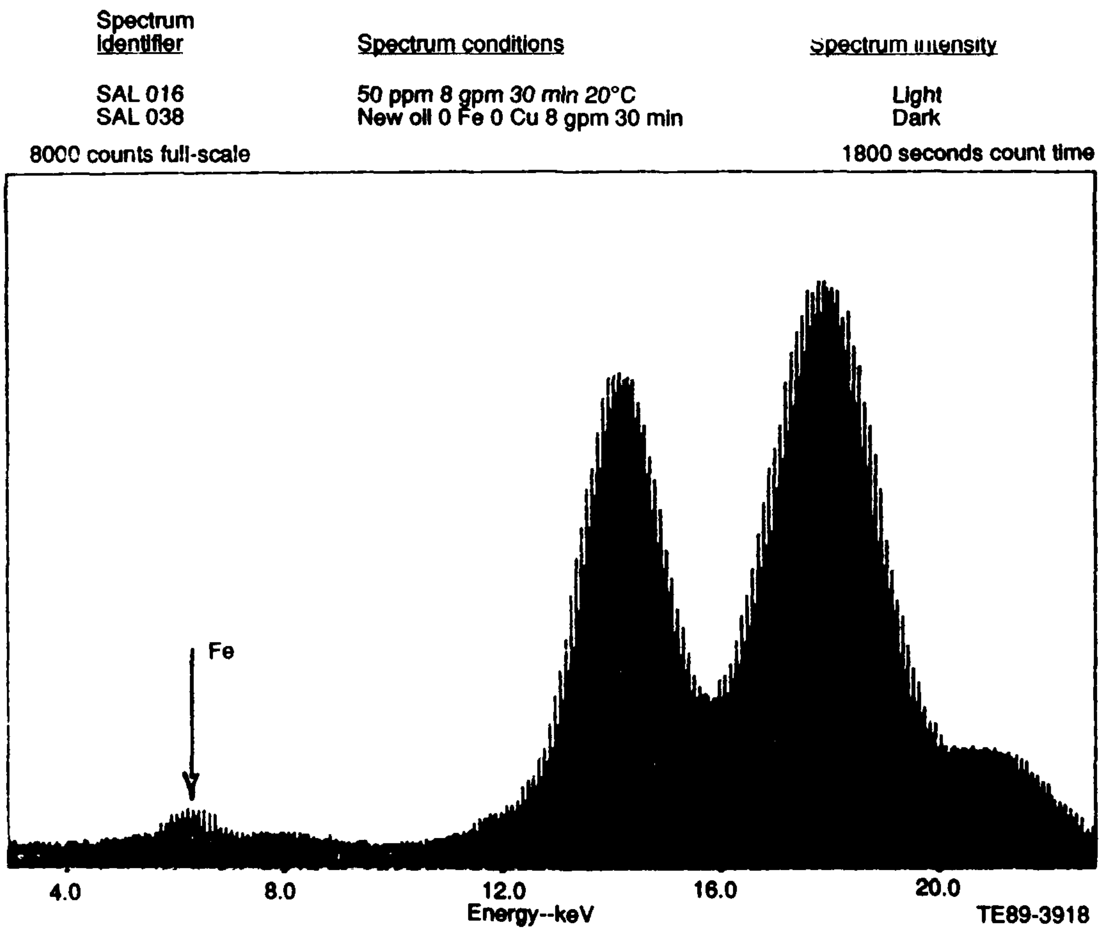

Figure 20. New oil spectra - static and 8 gpm flow rate.

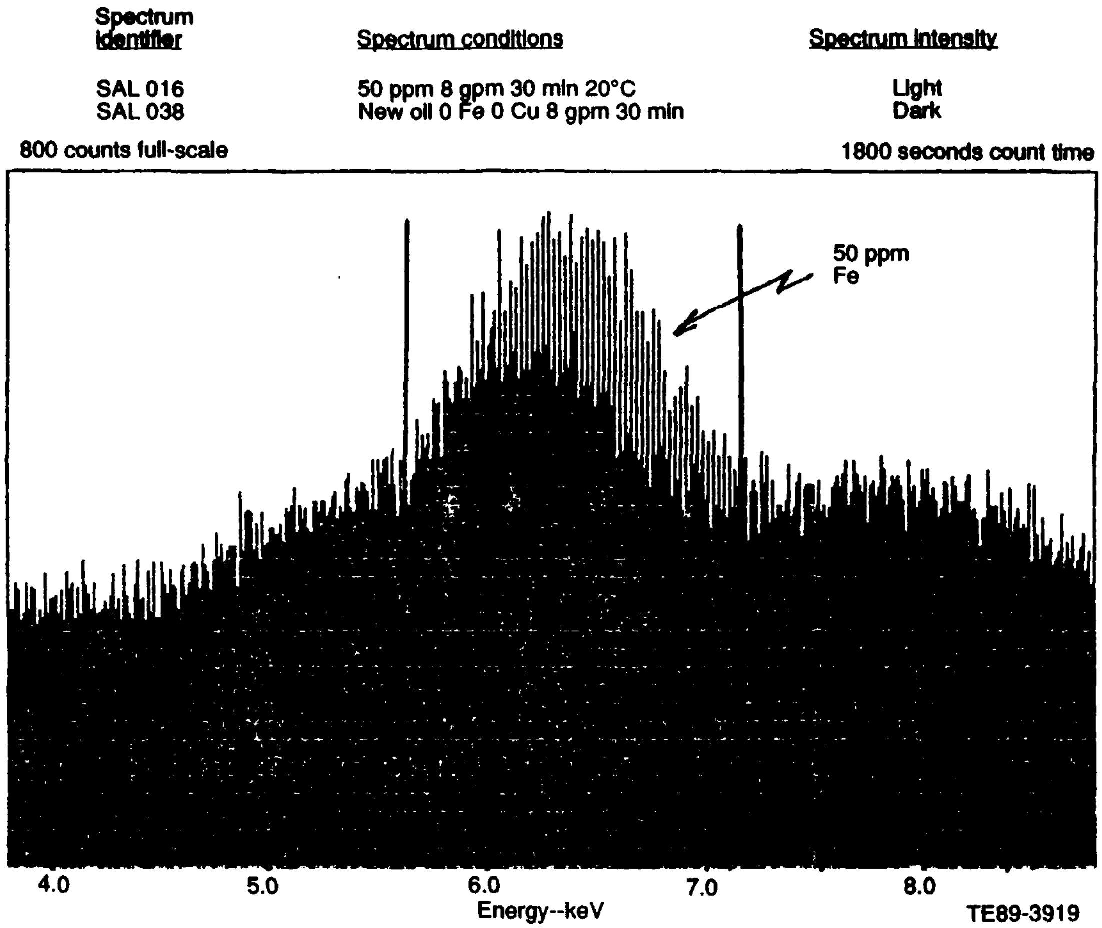

Figure 21. New oil and 50 ppm iron spectra - 8 gpm flow rate.

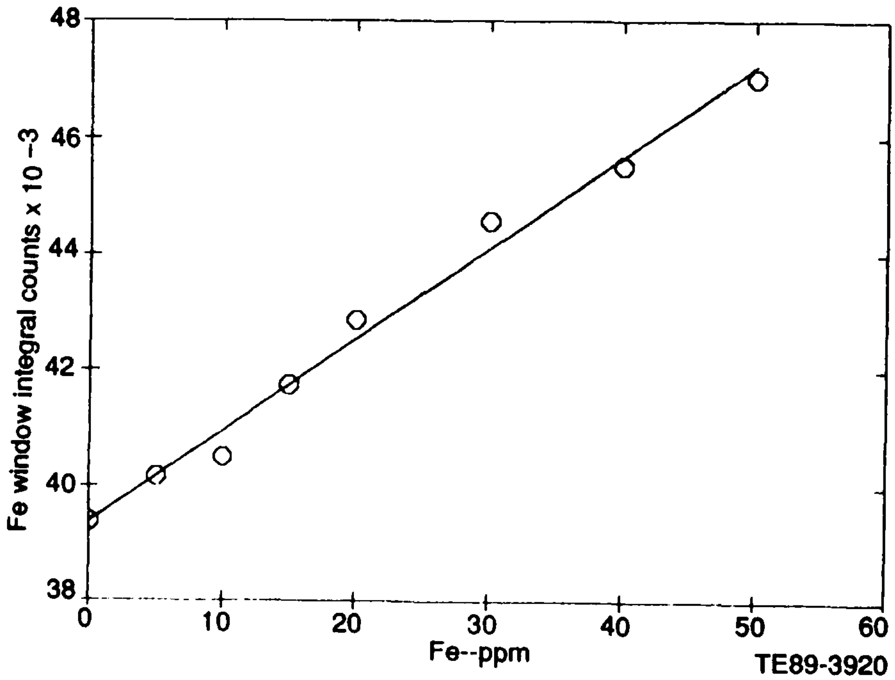

Figure 22. Iron counts versus iron concentration.

6.2 FLOW RATE EFFECTS

A 50 ppm iron contaminant level was analyzed at flow rates of 4 gpm, 7 gpm and 10 gpm. The air driven diaphragm pump would not run reliably below 4 gpm. Figure 23 shows the iron window integral data (on an expanded scale) plotted against pumping speed. The background (zero) level was 32,000 window counts and the actual analysis data varied from 15,562 to 14,716. The error bars indicate the one sigma statistical variance. The data trend was within 2 sigma statistics overall, and there is an overall difference of only 2.7 ppm iron at the detected 50 ppm level. It is therefore concluded that there is no significant effect of pumping speed on the sensor detection and analysis of the iron contaminant level. In further support of this is the fact that the pumping produced heating of the oil. Oil temperature thermocouples indicated that at 4 gpm, 7 gpm, and 10 gpm, the oil temperatures were 73°F, 78°F, and 89°F respectively; therefore, there is a temperature effect also involved in this data. Temperature effects are discussed in Subsections 6.5 and 6.7.

6.3 DETECTION OF LOW LEVEL COPPER IN THE PRESENCE OF IRON

After completing test runs with iron contaminant levels up to 50 ppm, copper contaminant (copper in oil standard from Conostan) was added to determine the sensor's ability to analyze low level copper in the presence of 50 ppm iron signal. The copper analysis curve is shown in Figure 24, with data taken to 10 ppm copper level. The spectrum of 10 ppm copper, 50 ppm iron, overlaid with base oil at 50 ppm iron is shown in Figure 25 which covers the region of the spectrum around the copper signal.

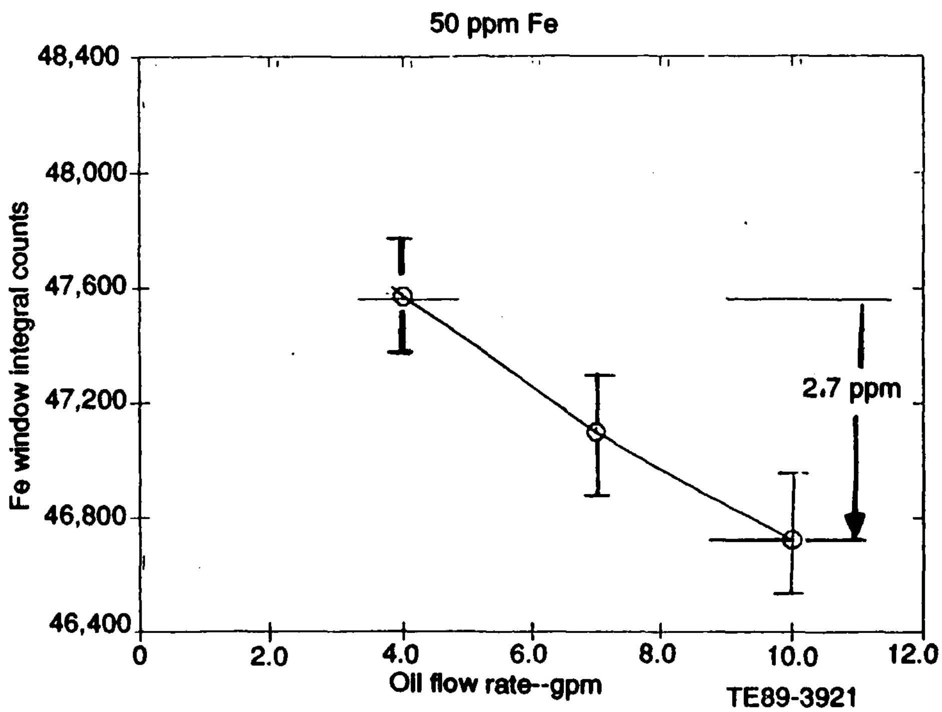

Figure 23. Iron counts versus flow rate.

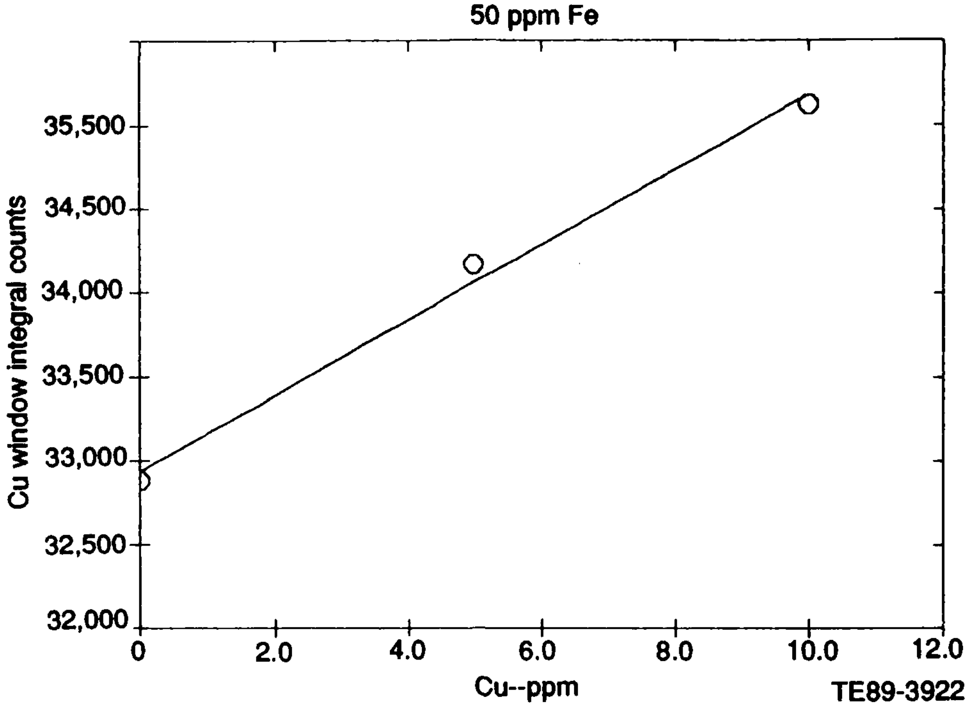

Figure 24. Copper counts versus copper concentration with 50 ppm iron.

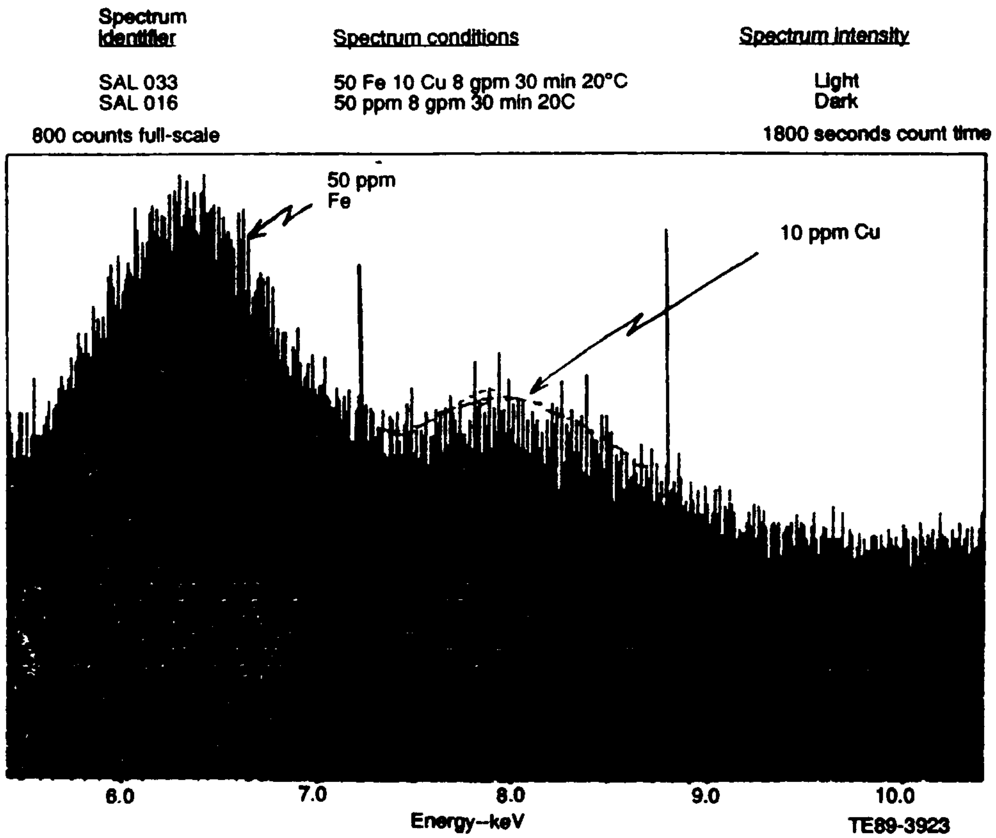

Figure 25. X-ray spectra - 50 ppm iron with and without 10 ppm copper.

Although this display does not visually indicate a strong response above background, the iron and copper peaks are separated well enough for analysis to be made, using fixed window regions, at these low levels of copper.

There is some overlap of iron and copper peaks, and a more sophisticated approach would be to deconvolute these peaks in software analysis of the spectrum data. However the system detected the copper trend correctly at the 5 ppm and 10 ppm levels.

6.4 DETECTION OF COPPER

For this investigation the oil contaminated with iron additives was drained from the flow system which was then flushed and loaded with fresh oil provided by Mobil Research Center, Pennington, NJ. Conostan copper standards in oil matrix were then added to generate known ppm copper levels in the oil. Oil samples were separately analyzed by the PGT Applications Group, with quantitative XRF equipment, throughout the runs.

Figure 26 shows the response of the sensor for copper analysis from 5 ppm up to 50 ppm. The solid line is a least squares fit to the data. Figure 27 shows the copper region in the spectrum of 50 ppm copper level compared to the base oil. The enhanced copper signal at 50 ppm level is very apparent and is also quite apparent in the total spectrum display, Figure 28. These data were taken at 8 gpm pumping speed. The residual iron peak is largely attributed to contaminant iron level in the beryllium window of the cell as discussed earlier. Copper analysis by the sensor is quite conclusive.

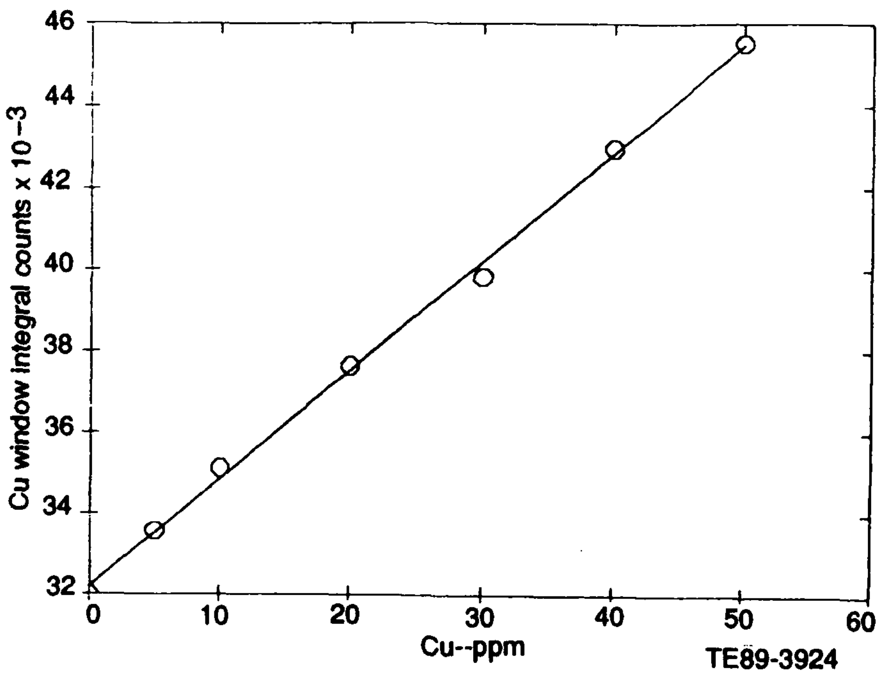

Figure 26. Copper counts versus copper concentration without iron.

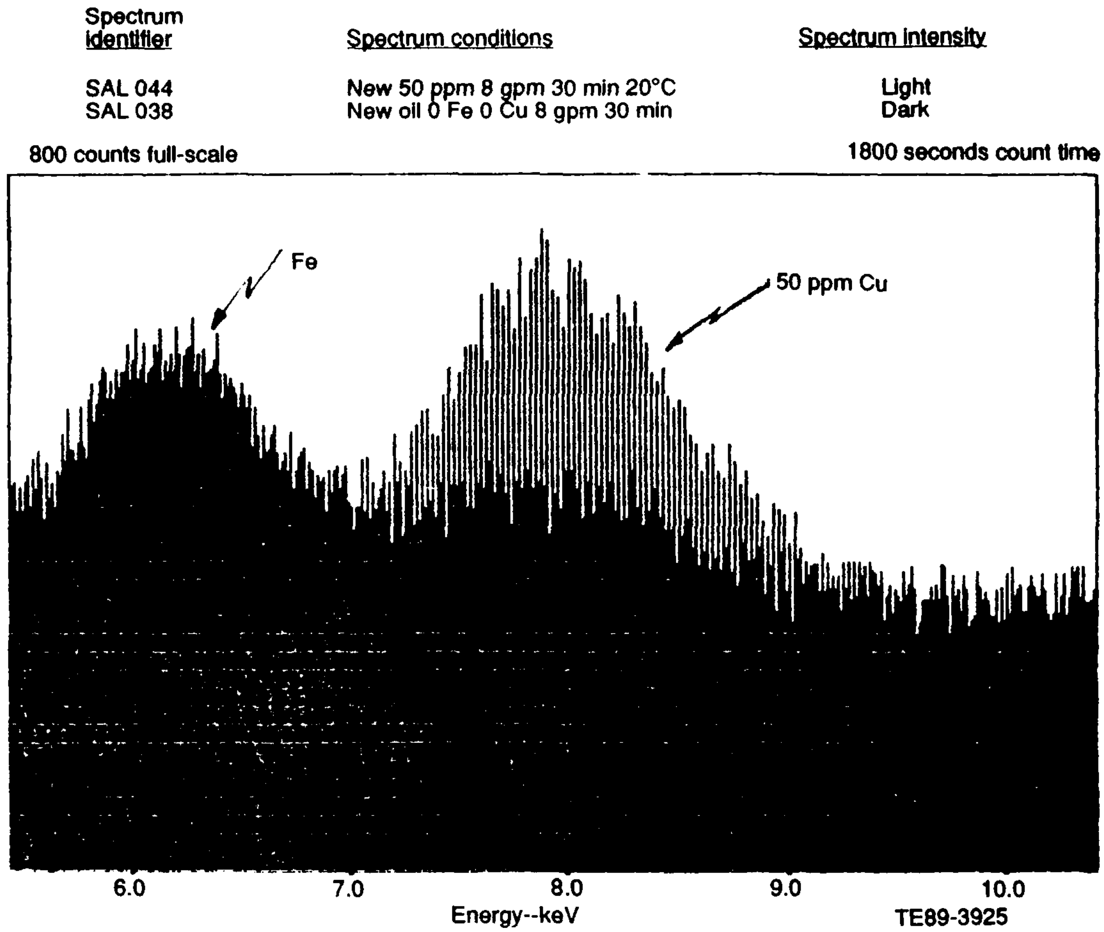

Figure 27. New oil and 50 ppm copper spectra - 8 gpm flow rate.

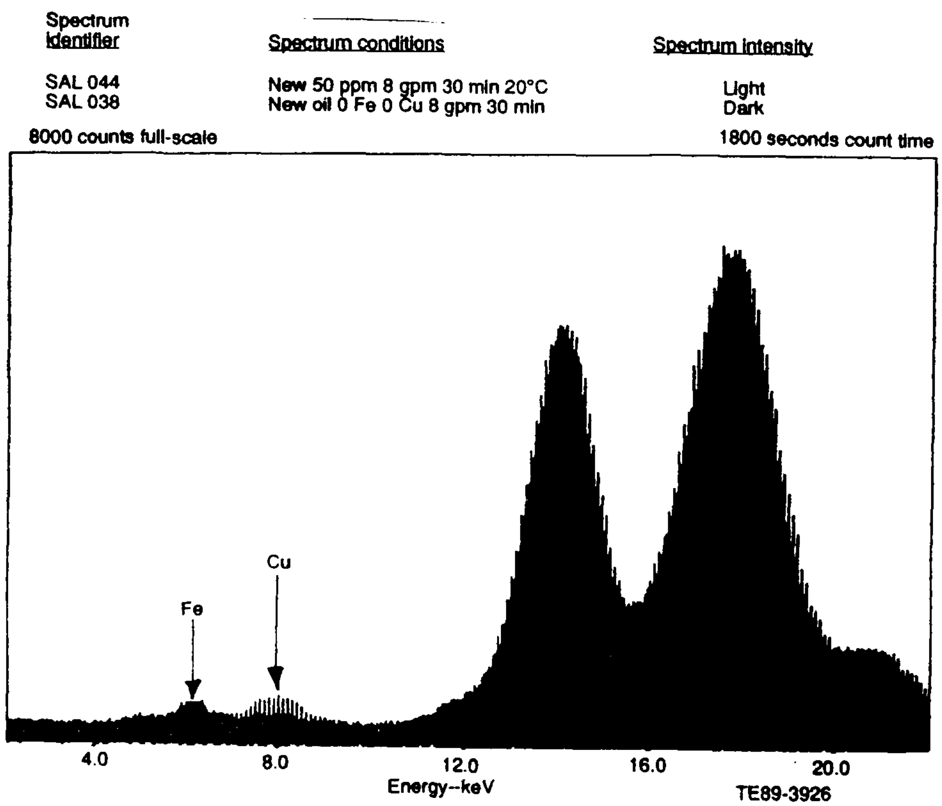

Figure 28. New oil and 50 ppm copper total spectra 8 gpm.

6.5 TEMPERATURE EFFECTS ON ANALYSIS.

In these tests the oil was circulated at a constant 8 gpm and oil temperature controlled from 20°C to 100°C. Figure 29 shows a curve of 50 ppm iron contaminant analysis at several temperatures. There is a decreasing trend with temperature. Oil expansion data supplied by Allison and values of oil density provided by Mobil Research Center, indicate around 5 percent expansion from 20°C to 100°C.

Since the sensor has essentially a fixed viewing area we expect to see some effect of the reduced oil mass being analyzed, due to volumetric expansion. There are some effects in the data that we cannot readily explain. For instance there is indication for a dip at the 60°C point. Although it can be argued that this is not much above 2 sigma statistics, it also shows on the completely separate analysis for 50 ppm iron, Figure 30.

The copper analysis is better suited to analyze this temperature effect than the iron analysis because it has a lower background level contamination in the copper region. In Figure 29, assuming a constant background level, the 50 ppm copper analysis at 20°C decreases by around 6 ppm at 100°C, so the overall temperature effect is not very large. However it is not solely due to expansion of the oil. There is a secondary effect which can also influence analysis. At the higher temperatures the electronic noise from the sensor is higher, and the system resolution is expected to worsen.

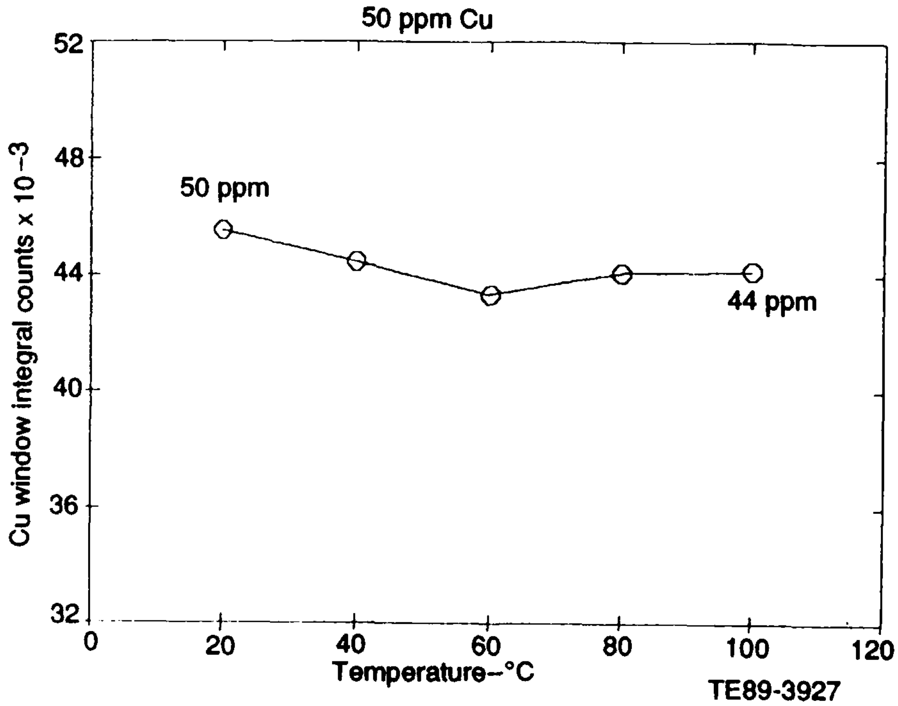

Figure 29. Copper counts versus oil temperature.

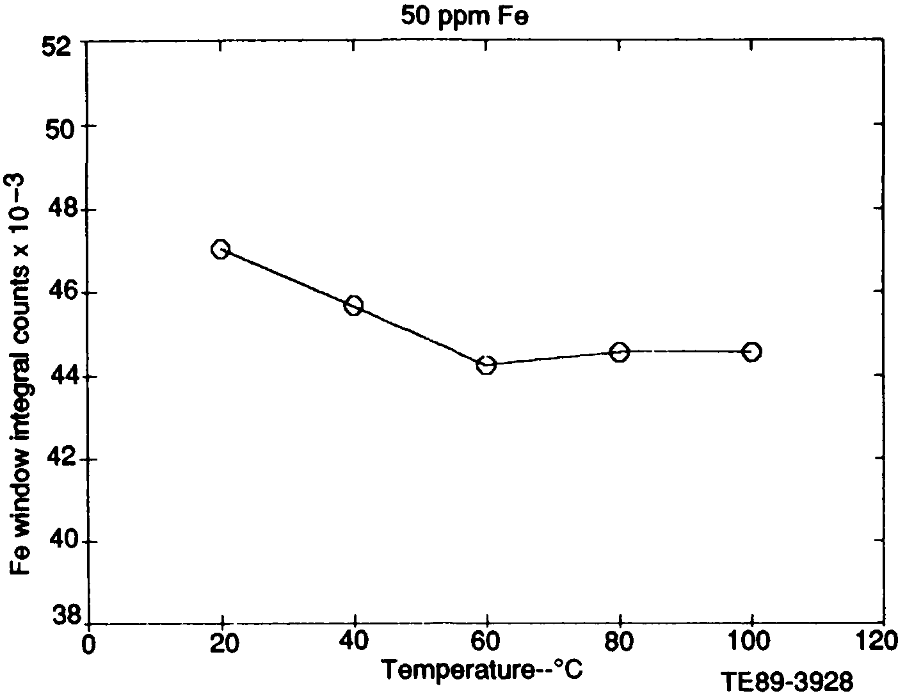

Figure 30. Iron counts versus oil temperature.

The main contributor to this effect is the increased leakage current of the field-effect transistor (FET) device which is on the front end of the preamplifier circuit and which connects to the X-ray detector tube. Such junction devices approximately double their leakage current for every 10°C increase in junction temperature. In early stages of this study, this effect on sensor performance was evaluated and devices and components were selected to permit operation above 125°C. However there is no way to prevent the increased noise at these temperatures and the worsening resolution associated with high temperature operation. For this reason the cell had been designed to thermally sink the electronics chamber to the oil temperature. This approach was taken to avoid the complexity of other schemes, such as cooling the sensor unit by making it a heat exchanger linked to the engine fuel supply system.

The sensor performance and stability with temperature had been recognized as primary initial concerns. The particular tests in this phase of the work relate directly to measurement of these effects, which are discussed further in Subsection 6.7. The effect of temperature on system resolution can be seen in Figure 31 in which spectra are compared for 50 ppm copper analyses at 20°C and 100°C operating temperatures. At 100°C oil temperature, the electronic thermal sensor in the analysis head indicated 90.5°C showing the sensor unit temperature is closely linked to the oil temperature.

The change in resolution can be seen, for example, in terms of the reduced peak height to valley region of the primary backscatter peaks, and the broadening of these peaks. The effect of peak broadening is to lose some analysis counts from the fixed window regions, causing an apparent decrease in recorded intensity of the analyzed contaminant. This situation can be seen in Figure 35, which is part of Subsection 6.7.

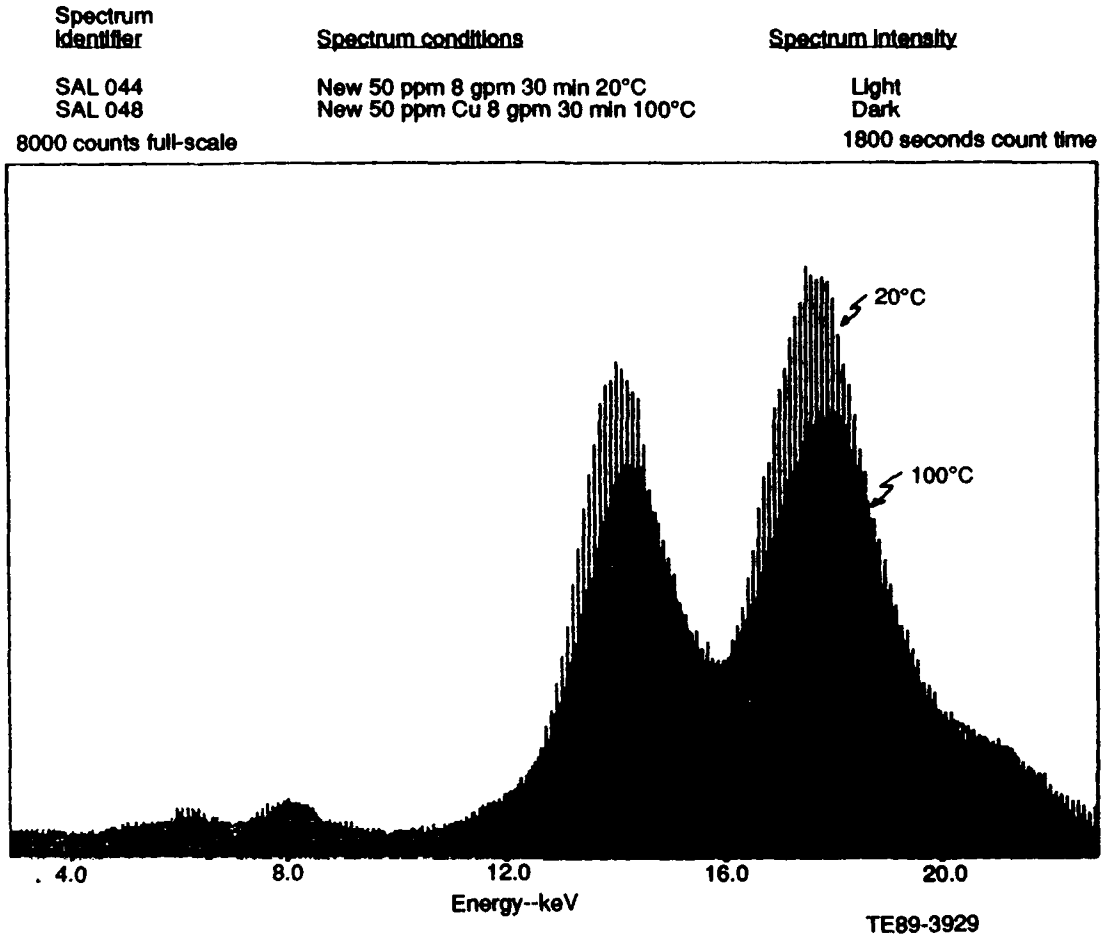

Figure 31. 50 ppm copper spectra - room and 100°C oil temperature.

6.6 EFFECTS OF AERATION

It had been stated that in actual engine conditions the oil is heavily aerated, and an attempt was made to investigate this effect. In previously shown data the oil was made to return to the oil hopper through a pipe below the oil level to avoid aeration as much as possible.

This was then changed to a high level return port above the oil level. Running under these conditions there was a noticeable foam layer on top of the oil in the hopper. Volume samples of oil were pipetted from below the surface and weighed with an electronic microbalance to see if aeration could be quantified in terms of weight loss in equal volumes of oil sample. No measurable weight losses were detected. This suggests the oil de-aerated rapidly below the oil surface in the hopper. Also, the Mobil Jet 2 MIL-L-23699 oil has antifoaming additives to minimize foaming.

In a later series of tests, analyzing copper impurity levels, strong aeration was deliberately introduced by forcing compressed air through an air stone immersed to the bottom of the hopper. Under these conditions a fine oil mist was produced above the surface of the oil in the hopper. Oil samples were tapped from the system downstream of the analysis cell and the samples indicated visually the presence of air bubbles which quickly cleared. However, analysis under these conditions showed no effects attributable to aeration.

Table 3 presents the results of the 50 ppm copper analysis performed at 8 gpm flow rate with the return pipe below the oil surface, and at 8 gpm flow rate with high level return port and addition of compressed air through the air stone in the oil tank.

TABLE 3. Iron Counts With and Without Foaming

Condition	Total count	Background count	Difference count	2 sigma	ppm analysis
a.	45,531	32,007	13,524	556	50 ± 2 *
b.	45,394	32,007	13,387	556	49 ± 2

* Based on known 50 ppm analysis curve

a. Flow rate 8 gpm at 20°C ambient, oil return below oil level with standpipe.

b. Flow rate 8 gpm at 20°C ambient, oil return from high port in hopper (standpipe removed) and compressed air also applied through air stone placed in the oil hopper.

6.7 TEMPERATURE EFFECTS ON THE SENSOR

In preparation for determining temperature effects, the sensor (cell unit) was equipped with a thin strip of copper foil across the cell window to obtain a spectrum typical of high level copper detection where the copper peak was of comparable intensity to the backscatter peaks.

The sensor was mounted in an environmental chamber purged with flowing nitrogen gas, and the temperature was varied from +100°C down to -50°C. The purpose of this test is to investigate the gain changes from the total engine mounted sensor unit consisting of the detector, preamplifier, amplifier and HV bias filter sections, over a wide temperature range.

The HV supply, which is very stable and which was independently temperature tested in the early design phases, is part of the SAU which would normally be fuselage or cockpit mounted, and which also contains the analog-to-digital converter and microprocessor control system.

A change of system gain over such a wide temperature range is expected. The important question is whether or not this gain change is small enough so that it can be treated as a perturbation to the HV bias setting for the detector so that closed loop gain control can be performed in the instrument by variation of HV bias to the detector.

Because proportional counter gain is very sensitive to the HV setting and HV stability, for closed loop gain control to work properly it is necessary that under initial settings the spectrum be "in place" so analysis can proceed. The computer then can recognize the two primary backscatter lines and initiate a calibration routine where HV bias is incremented or decremented by a small amount to bring the spectrum into correct position.

A knowledge of the gain change with HV detector bias value can be utilized by the computer in the iteration process to "zero in" rapidly to the correct operating conditions.

In Figure 32 and Figure 33 overlaid spectrum plots are shown for the sensor working at the two temperature extremes -50°C and +100°C. Figure 32 is the expanded display around the 8.00 KeV copper region, and Figure 33 is the full spectrum range display. The X-ray source backscatter peaks shift position more than the iron and copper peaks as a result of gain changes since they are at higher energy levels. For this reason, the backscatter peaks would be used for spectrum gain stabilization. This is a severe case. In practice one would expect the system temperature to assume a reasonably stable value, primarily related to engine oil temperature.

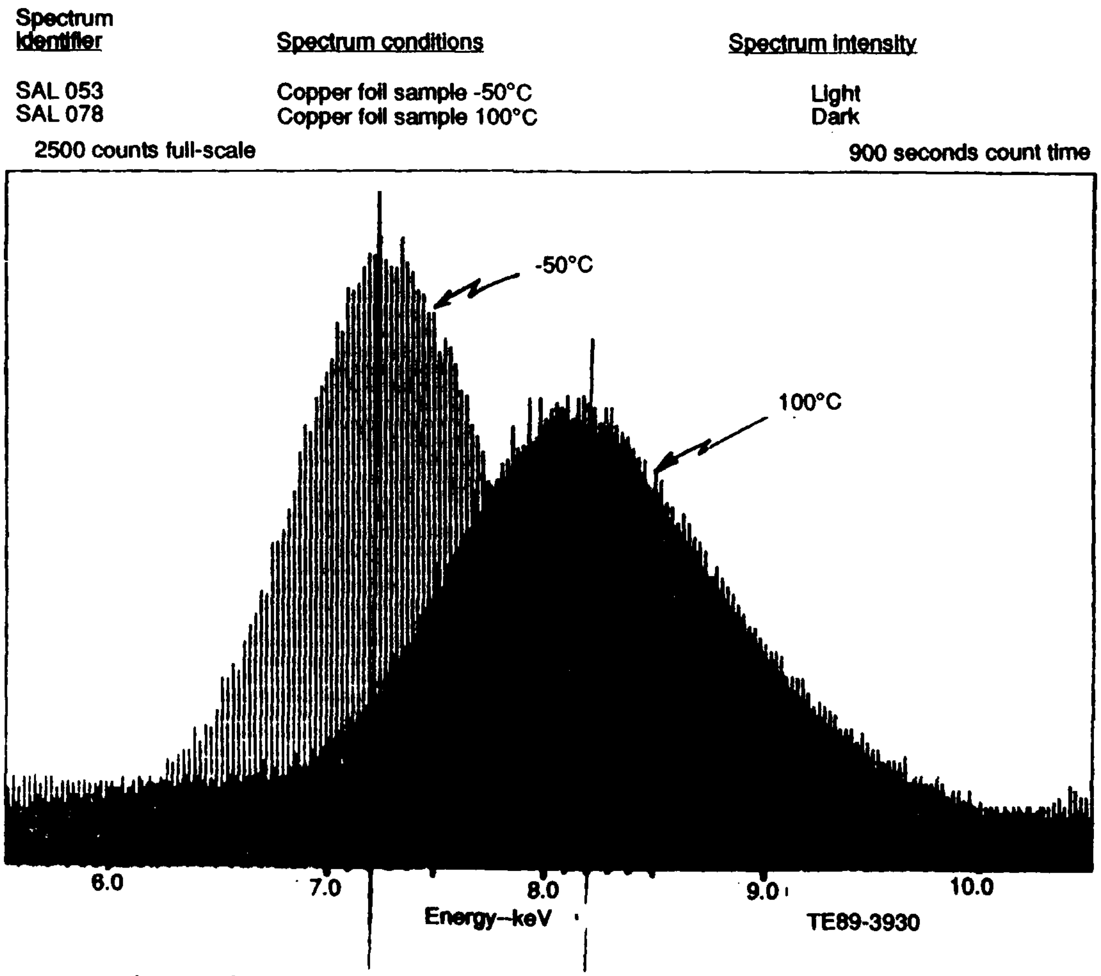

Figure 32. Copper foil spectra for 100°C and -50°C.

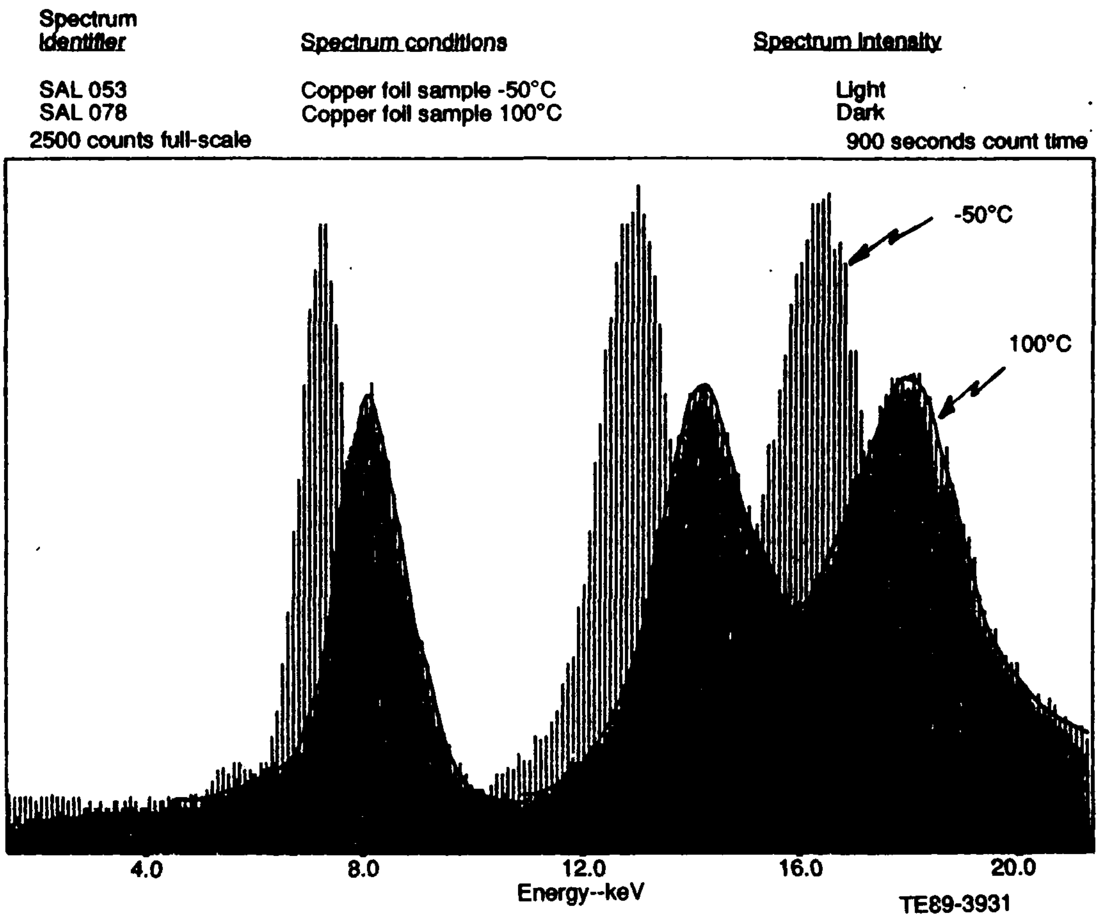

Figure 33. Copper foil total spectra for 100°C and -50°C.

The spectrum gain shift is most significant when going to the colder temperatures, and changes from room temperature (20°C) to 100°C are quite small. This is seen in Figure 34 for the total spectrum. In fact, from 20°C to 100°C the copper peak still remains inside the "analysis window" as is illustrated in Figure 35 which shows the extended display around the 8.00 KeV region. Therefore, in practice, no significant correction to the system is needed for 20°C to 100°C operation range.

The system gain change with detector HV bias is shown in Figure 36. In this case the position of the copper peak centroid (8 KeV) is at the nominal HV setting (574 volts), and peak energy position in the spectrum is then plotted as HV bias is changed by 10 volts in each direction. The curve should be smooth. The "wiggles" are due to uncertainty in visually determining peak centroid energy on the spectrum displays.

The ± 10 volt range is greater than what is needed for system control. Referring to Figure 32, at -50°C the copper peak centroid has moved down to around 7.20 KeV, and at +100°C has moved up to around 8.20 KeV. Transferring this shift to Figure 36, it is seen that this corresponds to a very small HV bias correction, namely around plus one or two volts above nominal value for the +100°C case, and around 4 volts below nominal value for the -50°C case.

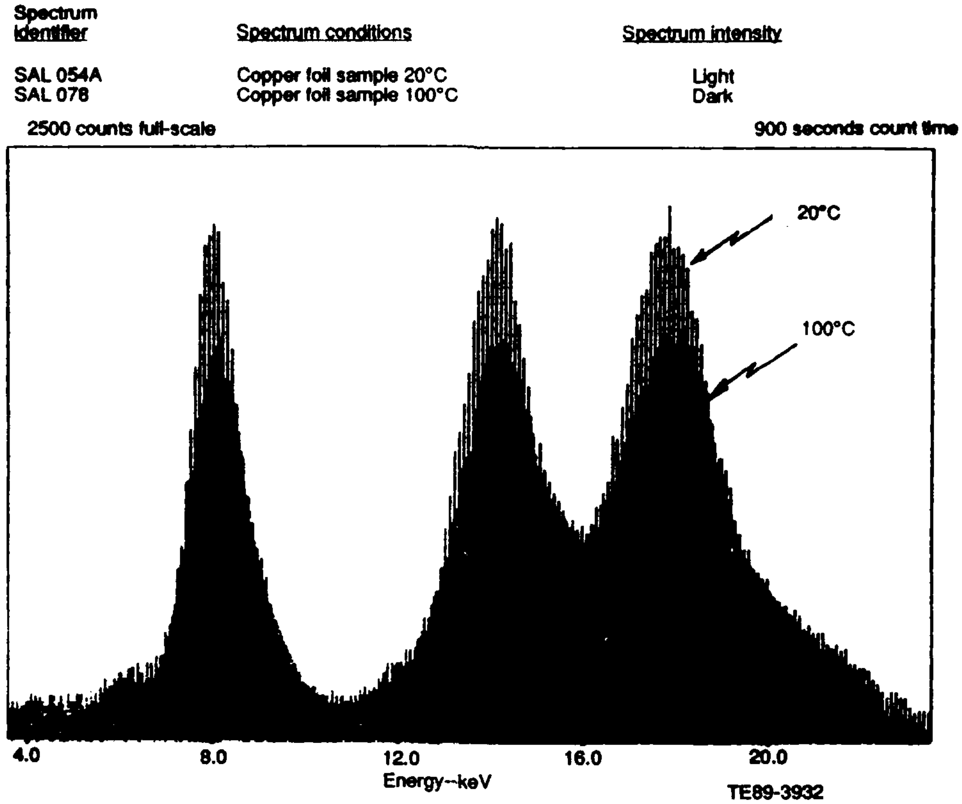

Figure 34. Copper foil total spectra for 100°C and 20°C.

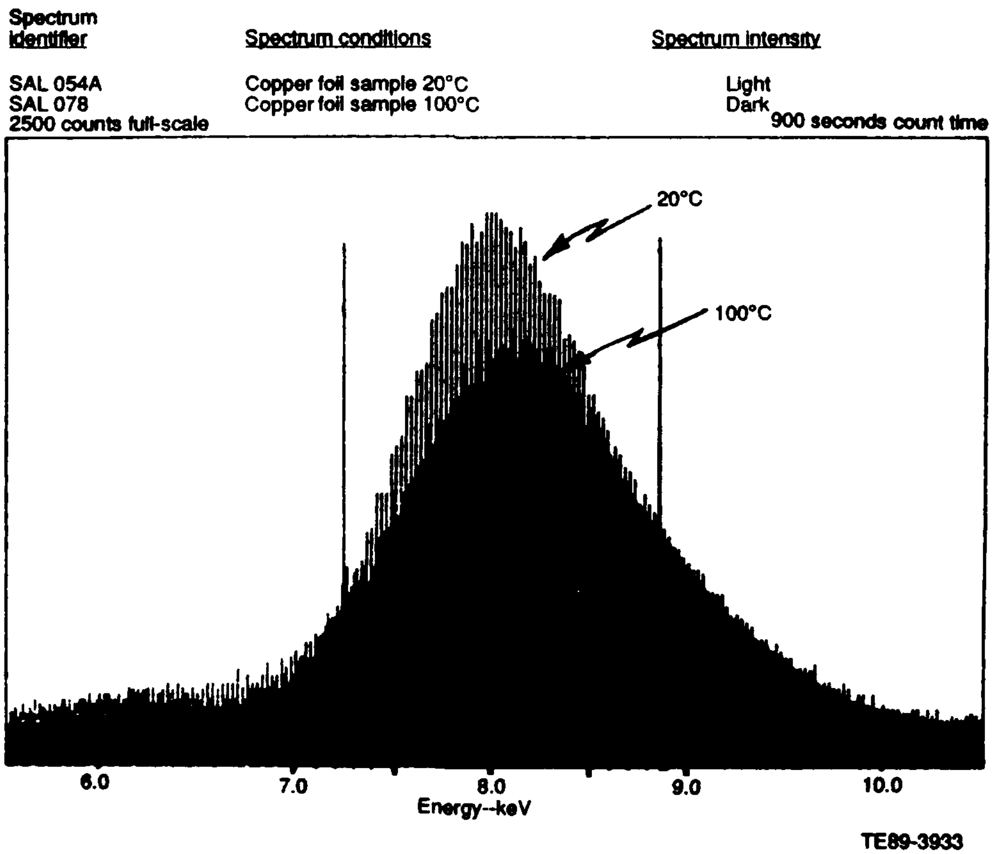

Figure 35. Copper foil spectra for 100°C and 20°C.

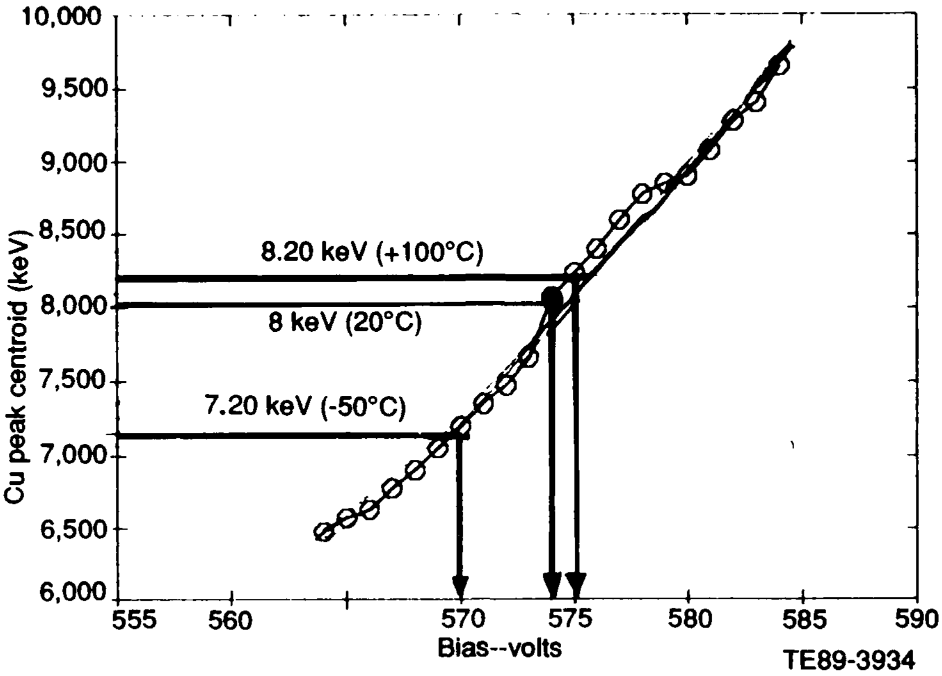

Figure 36. Copper peak centroid versus bias voltage.

The HV bias setting is monitored in the system, and can be read by the microprocessor computer. There are several ways in which the microprocessor analyzer can treat the data. With a stable system, such as this one, the analyzer can acquire data, identify the spectrum lines, and calculate the appropriate regions for iron and copper analysis. The other approach is to let the computer read and correct the sensor parameters to obtain stable spectrum positioning and then determine iron and copper from analysis of fixed window regions. The latter approach is favored mainly because of simplicity and to see if the sensor could do a reasonable job in a simple manner.

The sensor has been found to be very stable. For example, in the Allison engine test phase of this project, no settings were changed throughout the whole test period lasting several weeks. In the final system, the SAU's computer could control the detector HV supply based on a spectrum stabilization algorithm which would be checked periodically under software control.

In addition software could be developed to provide background subtraction under the iron and copper regions, and of course to calculate and correct for the overlapping of the iron and copper peaks.

Developing the software code for this degree of sophistication was beyond the scope of work in this contract, which was to develop and verify the performance of an on-line engine wear metal analyzer working at these low levels of detectability, to mount and test it on a working engine, and to provide analysis and output for logging and trend analysis.

VII. CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations based on the results of the In-Line Wear Monitor Program are described in this section. Some of the conclusions are based on the results of the work done prior to 30 June 1988, which is described in more detail in the Interim Technical Report (Reference 1).

7.1 CONCLUSIONS

The In-Line Wear Monitor Program has accomplished the following:

- A preamplifier circuit for conditioning and amplifying the signals from a proportional counter X-ray detector tube has been developed and shown to be stable at high ambient temperatures present on a turbine engine. The preamplifier front end has been redesigned to provide better mounting of critical front end parts and has been demonstrated to perform properly under actual engine test stand running.

- A high voltage power supply circuit for use with a proportional counter tube has been developed and shown to be stable at high ambient temperature.

- A sensor consisting of a flow cell that can be mounted on a TF41 engine, a miniature proportional counter tube, and miniature preamplifier and amplifier circuitry has been developed and demonstrated on a test stand engine.

- A SAU which processes the signals from the engine-mounted sensor has been developed and demonstrated during engine testing and oil flow bench testing. The SAU contains a peak detector, an analog-to-digital converter, a microprocessor based section for controlling the unit, high and low voltage power supplies, and system interface electronics.

- The ECA portion of a TF41 EMS has been modified to accept the new inputs from the In-Line Wear Monitor. The ECA was modified by using spare inputs so that none of its existing functions were disturbed. The TF41 EMS stores engine data on magnetic tapes for long term trending with a ground station.

- The In-Line Wear Monitor System has been evaluated on a TF41 AMT. The sensor was engine mounted and was tested for 272 hours of engine running. The engine test showed the wear monitor system can operate properly under test stand engine vibration and temperature conditions.

- The In-Line Wear Monitor has been evaluated on a flow test rig at various flow rates, concentration levels, oil temperatures and aerations. The wear monitor detected iron, copper, and both iron and copper together with less than 2 ppm one sigma statistical uncertainty for 30 minute count times over the 0-50 ppm range tested. There was no significant effect of flow rate or aeration on accuracy. The sensor was shown to change only 6 ppm when oil temperature was increased from 20°C to 100°C. This result was obtained with a constant HV supply. The change with temperature is

small enough that it can be corrected by closed loop gain control through varying the HV bias to the detector. The curve defining how the HV bias would have to be varied to correct the output over temperatures of -50°C to 100°C has been obtained.

7.2 RECOMMENDATIONS

The In-Line Wear Monitor System developed by this program is a major step forward since the sensor can be mounted on an engine and accurately detect both ferrous and nonferrous wear debris in the engine's oil. The continuous, in-line monitoring of wear debris enables early detection of problems, offers potential for reduced repair costs and downtime, and provides a valuable input for on-condition maintenance. The system has the potential to be expanded by the addition of other X-ray sources and detector gas mixtures to enable detection of other metals, such as silver, to help pinpoint the component causing the wear debris.

The following steps are recommended to advance the system to the point where it can be widely applied:

1. Incorporate the closed loop control temperature compensation of the HV bias supply so that temperature effects are further minimized.

2. Test the system in an actual flight environment to gain further confidence and to gather data for developing long term trending algorithms. The system can be most easily added to an A-7 aircraft with a TF41 engine utilizing an EMS. The sensor would be inserted in place of the tube between the oil tank and oil pump. The SAU would be mounted in the same compartment as the EMS and wiring added to interconnect the sensor, SAU, and the ECA of the EMS. Finally, the ECA would be replaced with the unit modified by this program.

   Alternatively, the system could be adapted to a different engine by modifying the flow cell of the sensor and either adapting to the existing EMS or adding the modified TF41 EMS components.

3. Develop the long term trending algorithms for the EMS ground station.

4. Develop a more compact, flightworthy version of the SAU. The SAU developed by this program utilized PC boards developed in other programs for some circuits, and wirewrap boards for new circuitry. The SAU could be built as a stand alone unit or as a board for incorporation in an EMS if the final application were known.

5. Expand the system data base by testing the wear monitor with other engines. The sensor can be easily added to engines on a test stand by the use of flexible tubing. For longer term evaluation, the flow cell could be modified and the sensor mounted on the engine.

The definition of what wear materials need to be moni:ored on each engine is a major consideration, as it may require the addition of other X-ray sources and detectors.

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